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UNIVERSITY OF ALBERTA

FACIES AND GEOMETRY OF THE SWAN HILLS MEMBER IN THE GOOSE RIVER FIELD, ALBERTA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

by

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Facies and Geometry of the Swan Hills Member in the Goose River Field, Alberta", submitted by Albert James Jenik, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The Upper Devonian Swan Hills Member and some associated rocks from the Goose River field, Alberta, were studied petrographically and paleontologically by examination of slabbed core and thin sections from eight wells. The geometry and paleotopography of the reef complex were studied by isopachous maps, structure maps and cross-sections.

The distribution of twenty-two facies within the reef complex indicates an atoll-like reef development in the Goose River field. Laminite and dismicrite rock types occur most commonly in the lagoonal part of the reef complex. Biocalcarenites and biocalcirudites with well developed porosity occur in the reef-rim positions.

The following lateral zonation of fossils is present:

1. Large stromatoporoids, brachiopods and crinoids occur in fore-reef positions,
2. organic-reef and near in-situ accumulation consists of *Stachyodes* and large stromatoporoids,
3. large stromatoporoids and *Stachyodes* are present in back-reef positions,
4. the lagoonal part of the reef complex consists mainly of *Amphipora* with some ostracods, forams and calcispheres.

An echinoderm-bryozoan-brachiopod coquina zone is present within the shaly carbonates of the Upper Beaverhill Lake Formation. Its site of deposition appears to be related to intra-reef and basinward channels.

The crest of the reef complex is located in the south-western part. The geomorphic features shown by maps and cross-sections are (1) outer slope, (2) gentle (?) back slope, (3) reef crest, (4) reef rims, and (5) lagoon. The isopachous map of the Dark Brown Submember shows three loci for initiation of Light Brown Submember growth.

Dolomitization and silica replacement are most strongly expressed in the fore-reef position and towards the base of the reef. Stylolites are very common and suggest considerable loss of original reef material.

ACKNOWLEDGEMENTS

This study was undertaken at the University of Alberta, Edmonton, during 1964-1965 under the supervision of Dr. J. F. Lerbekmo, and was supported by funds from the National Research Council.

The writer extends his gratitude to Imperial Oil Enterprises Ltd. for allowing him to examine slabbed cores in their Core Laboratory, Edmonton; to British American Oil Co., Ltd., Edmonton, for making available the slabbed British American Goose River 4-3-67-18 core, and especially to Mr. J. A. Pike for assistance rendered the writer during the course of this study. Appreciation is also expressed to Dr. A. D. Baillie of British American Oil Co., Ltd., Calgary for his help and co-operation. The writer is indebted to the Oil and Gas Conservation Core Laboratory, Calgary, Alberta for their aid in this study and for allowing the writer to sample core.

Mr. Frank Dimitrov did the drafting and photography of rock specimens and acetate peels. Mrs. Elizabeth Vincze made the thin sections and Miss Mae Patterson typed the final manuscript.

Finally, a special thanks to the many people who contributed by way of constructive criticism, lively discussion and helpful comments, and to my wife, Kendra, who spent many hours in the preparation of this manuscript.

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INTRODUCTION

General Statement

The discovery of Beaverhill Lake reefs was initiated in late January of 1957 by Home Oil in the Virginia Hills area. Then in the early spring of 1957, Home Oil made another discovery in the Swan Hills area, and Phillips 66 followed up with a discovery in the Kaybob area. The prolific Devonian of Western Canada now had a fourth producing petroleum zone - the "D-4" (named the Swan Hills Member by Fong, 1959). To date, all of the Beaverhill Lake reefs that have been discovered in the subsurface lie approximately in a square geographical area in central and west-central Alberta between longitudes 114 degrees (5th meridian) and 118 degrees (6th meridian), and latitudes 54 and 56 degrees north (see Figure 4). Proven petroleum reserves for these Beaverhill Lake reefs up to the end of 1963 are estimated at 918 million barrels (Committee on Slave Point and Beaverhill Lake Formation, Geological History of Western Canada, 1965).

Previous Work

Because of the economic interest in these Beaverhill Lake reefs, a number of studies have been carried out to better understand them. The following list attempts to summarize briefly in chronological order most of the published investigations:

Fong (1959), named the producing limestone unit within the Beaverhill Lake Formation the Swan Hills Member, and discussed its stratigraphic position.

Koch, (1959), (unpublished M.Sc. thesis), did a study on the correlation of the Swan Hills Member.

Fong (1960), enlarged upon his earlier paper (1959) and discussed Swan Hills reefing and hydrocarbon accumulations.

Fischbuch (1960), carried out a descriptive study of stromatoporoids of the Kaybob reef with the idea of using them as a correlative tool.

Carozzi (1961), carried out statistical measurements of organic and inorganic parameters from thin sections of one well in the Swan Hills field, and found a rhythmetical alternation of eight carbonate microfacies represented.

Edie (1961), carried out a facies study in the Swan Hills field and concluded that the Swan Hills Member consists of a "buildup" of successively smaller atoll-like layers.

Thomas and Rhodes (1961), did a textural and reservoir analysis of the Swan Hills Member in the Swan Hills area to illustrate the relationship of grain, matrix and cement variants of carbonate rocks to porosity and permeability determinations.

Fischbuch (1962), delimited three stromatoporoid zones within the Kaybob reef.

Brown (1963), did a study of some algae from the Swan Hills field and discussed their ecological importance.

McGill (1963), did a descriptive study of the ostracods from the Beaverhill Lake Formation.

Stearn (1963), carried out a study of stromatoporoids from the Swan Hills field and discussed their significance.

Murray (1964), completed a Ph.D. thesis study of the paleoenvironment and stratigraphic relationships of the Swan Hills Member in Judy Creek field.

Currently at the University of Alberta, Edmonton, a Ph.D. thesis is being written by G. M. Leavitt (on leave from Mobil Oil Co. Ltd., Edmonton) which concerns itself with a paleoecological and geochemical study of the Swan Hills Member in the Carson Creek North field.

Present Study

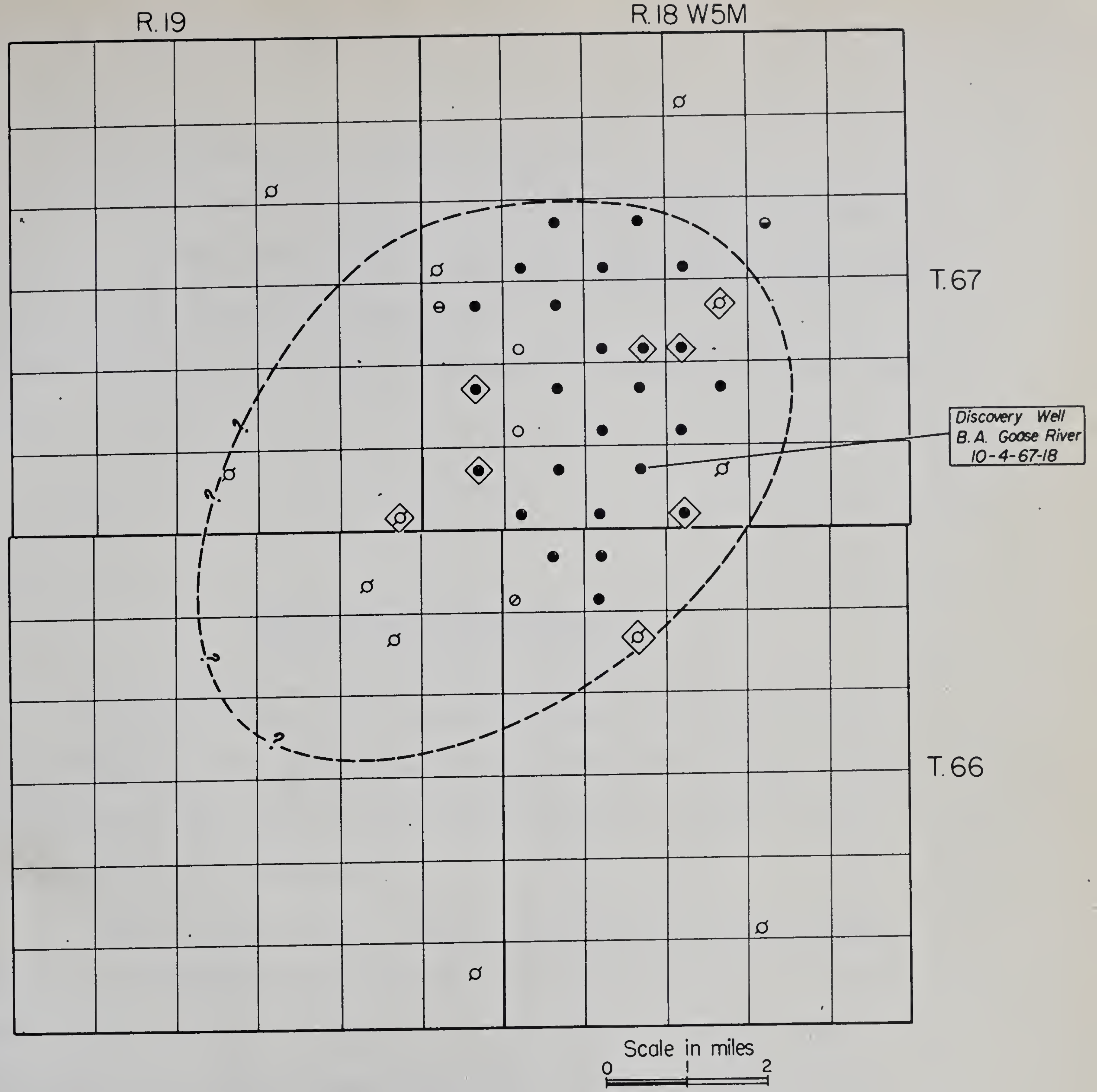
To date, the most recent Beaverhill Lake reef to be developed is located in the Goose River area, between the Kaybob and Snipe Lake fields. In 1963 British American Oil Co. Ltd., discovered oil in their British American Goose River 10-4-67-18W5M well (Figure 1). Development of the field has progressed until to date over twenty-five oil wells have been drilled on a two well per section basis. The writer was employed by British American Oil Co. Ltd., during the time of development of the Goose River field and had the opportunity to see core from a number of wells at which he was the well-site geologist. It was at that time, that he decided to carry out a facies study of the Swan Hills Member in the Goose River field. It is hoped that this study will add to the total picture of Beaverhill Lake reefs, and as Beales (1961) stated in his excellent paper, " .... much more work is still needed before we feel fully confident of our interpretations of ancient rocks".

OBJECTIVE

This study is primarily a paleofacies analysis of the Swan Hills Member across the Goose River field in a northeast-southwest line of section (see Figure 1). The study is primarily confined to the Light Brown Submember (see Figure 2) although the Dark Brown Submember has been investigated at the I.O.E. 2-1 and 10-15 wells. (The Dark Brown Submember is generally not adequately cored because the hydrocarbon reservoir is mainly confined to the Light Brown Submember). A "Coquina Zone" (see Figure 3) within the Upper Beaverhill Lake Formation was also described. By a petrological and paleontological study of slabbed well cores the writer has attempted to show:

(1) the distribution of different rock facies throughout the reef complex,

(2) the distribution of various organisms throughout the reef complex,



LOCATION MAP

Figure 1.

(3) an interpretation of paleoenvironments,

(4) the relationship of porosity distribution with respect to geomorphic position within the reef complex and hence to different facies, and

(5) an interpretation of reef growth.

A description of stylolites was also undertaken and their significance commented upon.

METHOD OF INVESTIGATION

An approach similar to Klovan's (1964) Redwater reef complex analysis was undertaken but on a smaller scale (also see Murray, 1964). Figure 1 shows the location of wells which were examined by the writer, and Table 1 gives some pertinent data on these wells.

These particular wells were chosen because they were thought to represent various paleogeomorphological positions within the reef complex (and hence different facies), and also because the core was already slabbed (the British American 10-3-67-19 and Imperial Goose River 12-23-67-18 wells were only used as control wells to illustrate the shape of the reef complex). Cores were examined at the Oil and Gas Conservation Board Core Laboratory in Calgary, Imperial Core Laboratory in Edmonton, and in the British American Core Storage Room in Edmonton. Sampling could only be carried out on core which was stored in the Oil and Gas Conservation Core Laboratory, which was done after the core was examined at the other two places which were more accessible to the writer. Only two of the wells examined had cored the complete Swan Hills Member; viz., the I.O.E. 10-15-67-18 and I.O.E. 2-1-67-19W5M wells.

TABLE 1

WELLS EXAMINED

Well name and location	K.B.	Status	Top Swan Hills Member (Gamma Curve)			Cored Interval logged
			Elevation	Subsea	Corrected	
B.A. Goose River 10-29-66-18W5M	2474'	D & A	9237'	-6763'	-6606'	9230-9260
B.A. Goose River 4-3-67-18	2666'	B.H.L.* oil well	9310'	-6644'	-6539'	9230-9415
Imp. Goose River 10-6-67-18	2534'	B.H.L. oil well	9177'	-6643'	-6463'	9160-9314
Imp. Goose River 10-7-67-18	2472'	B.H.L. oil well	9080'	-6608'	-6448'	9070-9167
Imp. Goose River 4-15-67-18	2630	B.H.L. oil well	9142'	-6512'	-6448'	9180-9320
Imp. Goose River 10-15-67-18	2669'	D & A	9252'	-6583'	-6555'	9260-9407
Imp. Goose River 2-16-67-18	2584'	B.H.L. oil well	9124'	-6540'	-6459'	9119-9256
Imp. Goose River 2-1-67-19	2467'	D & A (S.W.)	9124'	-6657'	-6432'	9110-9447

* may also be producing from "Coquina Zone"
B.H.L. - Beaverhill Lake

Table 2 shows the data sheet (modified from Klovan, 1964) which was used to log the different parameters in this facies analysis. Such parameters as relative fossil abundance, degree of fossil wear, ratio of spar to mud, and nature of grain types were recorded. A grain percentage estimate chart (Terry and Chilinger, 1955) was used to estimate the percentage of grain types in the rock. Amount of fossils is also based on visual estimation. The terms absent, rare, common and abundant are used to describe the occurrence of a given fossil relative to its occurrence in other parts of the reef (see also Klovan, 1964, p. 34).

TABLE 2

DATA SHEET

FACIES ANALYSIS OF THE GOOSE RIVER REEF COMPLEX	
WELL:	UNIT INTERVAL:
KBE:	UNIT THICKNESS:
1. MACROSCOPIC FEATURES	Rounding of grains:
Lithology and Colour:	Packing of grains:
Impurities:	Ratio of Grain/Micrite:
Vugs:	Matrix:
Fractures:	Cement:
Stylolites and Nature of Material:	Ratio of Spar/Mud:
Texture and Fabric and Structure:	Other Authigenic Minerals:
Porosity:	Comments:
Comments:	3. PALEONTOLOGICAL DATA
2. MICROSCOPIC FEATURES	Est. percent total fossils:
Mean grain size and type predominant:	Distribution of fossils:
	Degree of wear of fossils:
Nature of grains and amount est. and average grain size: Skeletal:	Relative abundance of fossil types:
Non-skeletal:	

Core slabs were studied under binocular microscope after having been etched with ten percent hydrochloric acid and smeared with liquid petrolatum (Russian Oil). This procedure brought out the textural detail on the rock surface. At the same time that the parameters of the different facies were being logged on the data sheet, a litholog was prepared with notations as to where thin sections, polished sections and acetate peels should be made. The Oil and Gas Conservation Board allowed one cubic inch of sample per foot of core to be taken, and it was from here mainly that samples for thin sections and polished sections were obtained. Imperial Oil Enterprises Ltd., and British American Oil Co. Ltd. allowed slabs to be taken to the University of Alberta, Edmonton, where polished sections and acetate peels were made.

All of the laboratory work was carried out at the Geology Department, University of Alberta, Edmonton. Staining techniques (see Appendix 1), were used to differentiate calcite from dolomite). Thin section and acetate peel studies (see Appendix 2 for acetate peel technique) were carried out under the petrographic microscope. X-ray work and insoluble residue analysis were begun, but it was found that they would need to be complete studies within themselves, and had to be abandoned. The geometry of the reef complex was studied by structure and isopach maps and various cross sections. Mechanical logs were examined in the hope of tracing facies laterally through the reef complex, but this proved to be unsuccessful.

STRATIGRAPHY

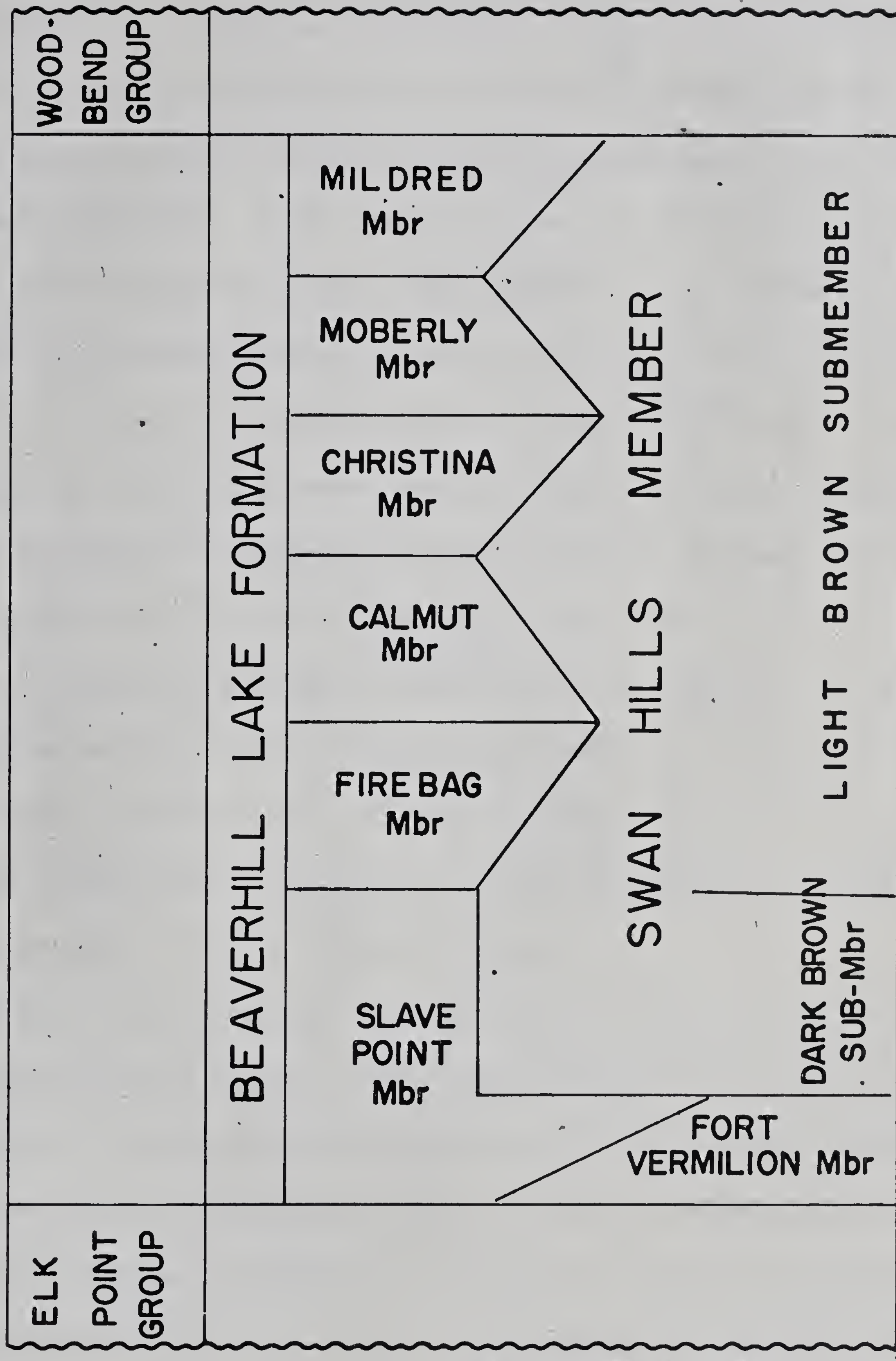
Nomenclature and Brief Historical Review

The Beaverhill Lake Formation was named in the subsurface by the Imperial Oil staff (1950) and the type section was designated in the Anglo-Canadian

Beaverhill Lake No. 2 well (Lsd 11-11-50-17W4M). This formation overlies the Elk Point Group (named by McGehee, 1954) disconformably and underlies the Woodbend Group with gradational contact in central Alberta (see Figure 2). In 1950, three shale-limestone cycles were recognized, and in 1957 Crickmay (also see Norris, 1963) officially named these as six members (Figure 2). Warren and Stelck (1950), on the basis of corals and brachiopods, correlated the Beaverhill Lake Formation with the Waterways Formation (named by Warren, 1933) which is found to the north and northeast of the Peace River Arch.

During 1957 oil was discovered in reefal limestone within the Beaverhill Lake Formation. As the Lexicon (1960, p. 339) states, "the name Slave Point Formation was used to designate the carbonate unit in the area southeast of the Peace River Arch", but because of lack of proof of stratigraphic continuity with the Slave Point type section, the name Swan Hills Member was proposed by Fong in 1959. The type section for the Swan Hills Member was set up in the Home Regent "A" Swan Hills 10-10-67-10W5M well (see Fong, 1959 and 1960 for description and further discussion of the type section). It is interesting to note that Murray (1964) proposes that the name Beaverhill Lake Formation be dropped and that the Swan Hills Member be elevated to formation status as part of the Waterways Formation.

Belyea (1957, p. 6) said that, "the Beaverhill Lake Formation is probably represented by the Basal Fairholme beds (Flume Formation) in the mountains and that it thins to the south and consists of carbonates and associated evaporites". She also stated that, "the progressive thinning of the Beaverhill Lake Formation westward (see also Fong, 1960, Figure 5, p. 199) as well as southward, and the transition from shale-limestone lithology in the Southern Plains suggests a shoreline not only to the south, as indicated by Andrichuk, but also to the southwest and west".



after Committee on Slave Point and Beaverhill Lake Formations from Geologic History of Western Canada (1965)

BEAVERHILL LAKE STRATIGRAPHIC SECTION IN WEST CENTRAL ALBERTA

Figure 2.

Fong (1959, p. 102) says that, "the Swan Hills Member is an organic and bioclastic limestone unit overlying with gradational contact anhydrites and shale beds of the "basal" Beaverhill Lake Formation (see Figure 3) and underlying dense, dark brown to olive-grey limestone and dark olive-grey and dark grey to brown shale of the Upper Beaverhill Lake". In this thesis the upper part of the Beaverhill Lake Formation is referred to as the "Virginia Hills Member" in areas where the Swan Hills Member is present (see Figure 3). This is a term widely used in the petroleum industry but has not been seen by the writer in any published literature. Fong, 1960, refers to the anhydrite-dolomite-shale unit below the organic limestone (Dark Brown Submember) and above the Gilwood sandstone as "basal" Beaverhill Lake. The writer also concurs in this usage (see Fong, 1960, p. 199 for further discussion). Following Fong (1959, p. 102) the Swan Hills Member is divisible into two informal units on the basis of colour and lithology; "a Lower Dark Brown unit and an Upper Light Brown unit. The two interfinger near the facies boundary, and each unit contains some beds similar in facies to the other". The Light Brown and Dark Brown units are now of submember status.

The Dark Brown Submember may be correlative (time-wise) to the Slave Point Member (named by Cameron, 1918) in part (see Figure 2). If this is so, and since Norris (1962) places the Slave Point in the Givetian Stage (Middle Devonian), then part of the Beaverhill Lake Formation is of Middle Devonian age. It appears then that the Dark Brown Submember is a facies of the Slave Point in part (see Figure 2). Occurring in the subsurface of northeastern Alberta is the Fort Vermilion Formation (Law, 1955) which consists mainly of anhydrite and is equivalent to the lower part of the Slave Point Formation. The Slave Point, like the Beaverhill Lake, exhibits shale basin - carbonate shelf relationships with development of highly porous dolomite belts along the shelf front facies (Geological History of Western Canada, 1965, p. 221).

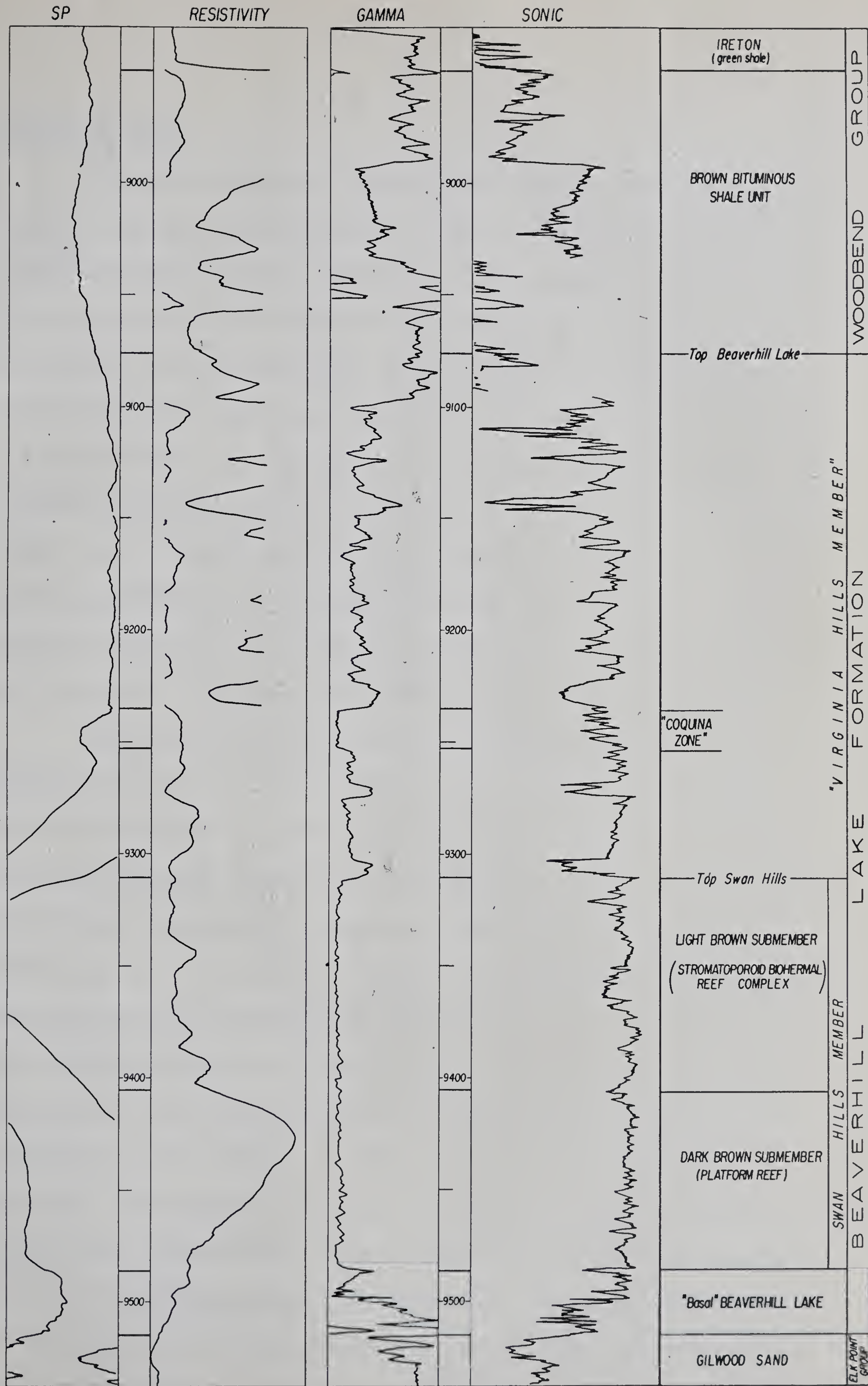


Figure 3.

MECHANICAL LOG TOPS

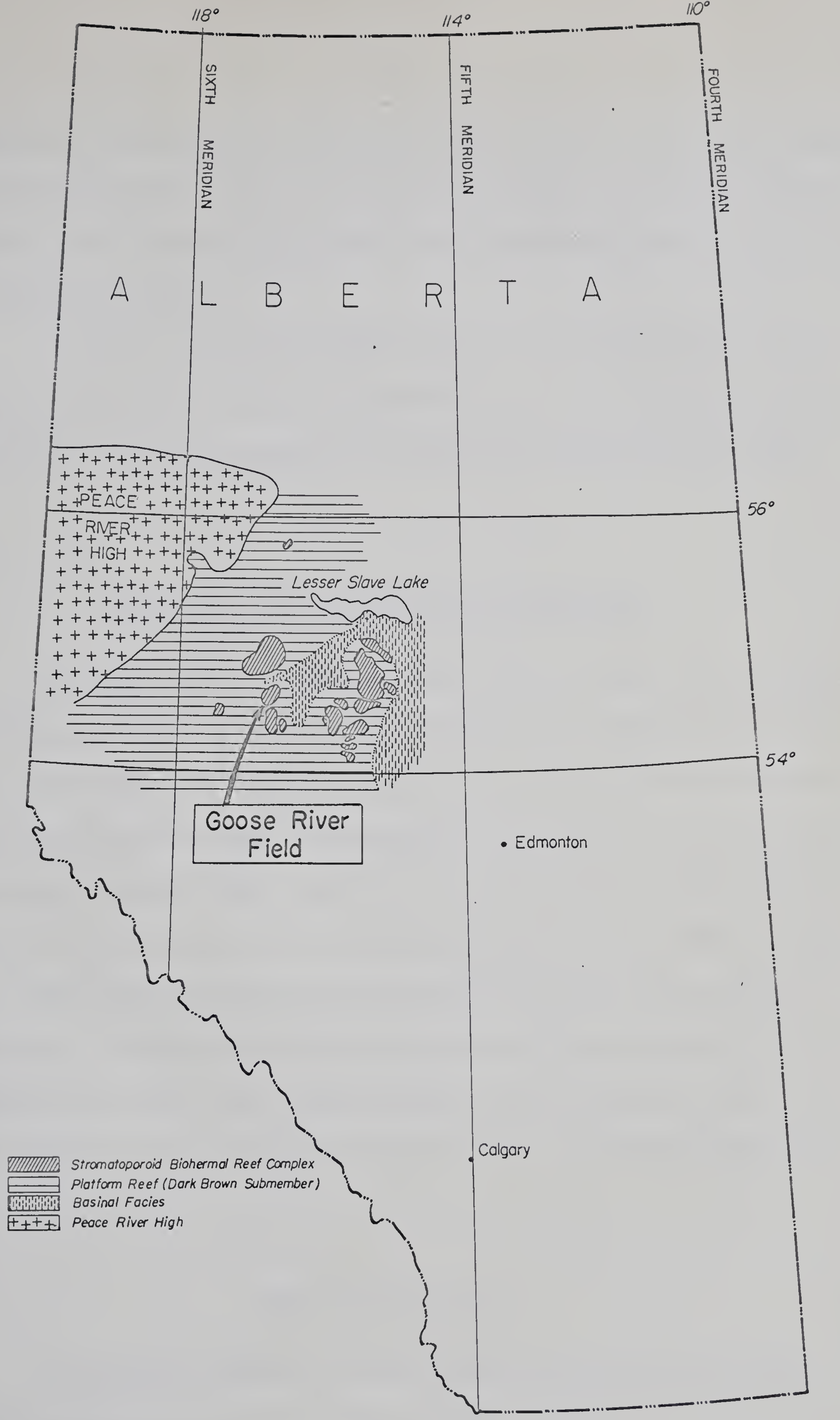
B. A. GOOSE RIVER

4-3-67-18

Geological History

Prior to the deposition of Beaverhill Lake sediments in the central Alberta area, Elk Point sedimentation ended with deposition of evaporites and red beds in a restricted basinal environment. Webb (1954, p. 13) states that, "There is evidence of an erosional unconformity between Middle and Upper Devonian time. On the north flank of the Peace River Ridge, an arkosic sandstone member (the Gilwood Sandstone) generally intervenes between the top of the Elk Point Formation and the overlying carbonate rocks of the Upper Devonian (Beaverhill Lake Formation). This sandstone undoubtedly represents outwash from the Peace River Ridge perhaps due to a slight renewal of uplift and rejuvenation of erosion in that positive area. The general post Middle Devonian emergence was brief, but allowed time for slight eastward truncation by erosion before the great transgression of the Upper Devonian sea commenced". Warren and Stelck (1950) also agree that this break exists.

During Beaverhill Lake time there was a marine transgression in which argillaceous and marine limestones with shales were deposited in a basin to the east of the Peace River High with local biohermal reef development in the shelf area in the vicinity of the Peace River High (Figure 4). To the northwest the Swan Hills Member is terminated by onlap onto this High (Fong, 1960, p. 203). Fong further states that to the southwest, the Swan Hills Member interfingers with reef dolomites underlying the Windfall reefs of Woodbend age. In central Alberta then, the Beaverhill Lake Formation is represented by cyclical repetition of carbonates and shales which pass laterally to shales in Northern Alberta and carbonates and evaporites in Southern Alberta. In 1957, when the Swan Hills Member was discovered, Fong suggested a reef origin for it because of the general shape of the mass, steep dipping flanks, and abrupt nature of interfingering facies contact with the surrounding dense shaly beds. Since 1957, further Beaverhill Lake reef discoveries have proven Fong's interpretation correct. Figure 4 shows the distribution of these Beaverhill Lake reefs in central Alberta. The Swan Hills Member



DISTRIBUTION OF BEAVERHILL LAKE REEFS

Showing Paleogeology in West Central Alberta

SCALE IN MILES

0 20 40 60 80 100

—adapted in part from Geological Atlas-1965 & Murray-1964, unpublished PhD. thesis

Figure 4.

represents the first episode of reefing in the Upper Devonian of west central Alberta. In Lower Woodbend time there was a pronounced increase in the rate of subsidence within the basinal area east of the Peace River High and reef growth continued also into Cooking Lake time.

In summary, the end of Middle Devonian time is represented by broad emergence and erosion, followed in Upper Devonian time by subsidence and marine transgression with reef development on the shelf area off the Peace River High.

REGIONAL SETTING OF GOOSE RIVER FIELD

The Goose River field is located about thirty air miles to the southeast of Valleyview, Alberta, (Figure 1) and is situated between the Snipe Lake and Kaybob fields along a north-south Beaverhill Lake reef trend on the southeastern flank of the Peace River High. The approximate reef outline covers Twp. 66 and 67 and Range 18 and 19W5M. Areawise it is similar to Kaybob, Swan Hills South, and Judy Creek. Drilling in the area has progressed to the state where the Light Brown Submember (a stromatoporoid biohermal reef complex) can be delimited (see Figure 1). Production is limited to the eastern half (updip portion) of the biohermal reef complex which covers an area of about forty square miles. The regional dip in the area is about forty feet per mile in a southwesterly direction.

REEF TERMINOLOGY

Regarding the definition of a reef, the writer follows Klovan (1964). Hence the following definitions are adhered to:

reef complex – the aggregate of reef limestones and related carbonate rocks

reef - a rigid carbonate structure with vertical dimensions significantly larger than the contemporaneous sediments, composed, at least in part, of organisms able to build and maintain the structure as a topographic feature on the sea floor and potentially in the zone of wave action.

organic reef - that portion of the reef which is or was built directly by organisms, and is responsible for the reef's wave-resistant character.

In this study the Light Brown Submember is considered to be a "biohermal reef complex", (the word bioherm denotes shape of the reefal mass) and the Dark Brown Submember to be a "reef platform" (see Fong, 1959). Murray (1964) refers to the Swan Hills Member as a reef fringed carbonate bank which developed in the argillaceous limestones and shales of the Waterways Formation. This implies that the organisms were not capable of building a "wave-resistant ridge". Evidence suggesting that the Swan Hills Member in the Goose River field is a reef is found in structural and isopachous maps, lateral fossil zonation and biocalcirudite limestone talus deposits. Feray, et al. (1962) recognize two distinct categories of biogenetic rock types which they call accretionary and aggregational accumulations. Accretionary deposits are the true reefoid carbonate buildups, while aggregational build-ups are composed of the in-situ accumulation of skeletal debris in association with other particle types. Organic reef in positions of growth is of doubtful interpretation in most ancient limestones. Aggregational build-ups may or may not develop into mound-shaped deposits, but they are never transported and deposited by currents.

In the Goose River area there is present, in two wells, a lens-like, twenty-foot-thick accumulation of biogenic material consisting of coarse calcarenite size fragments of crinoids, echnoids, bryozoans, algae and brachiopod valves cemented by clear sparry calcite. Scattered one to two foot intervals of

inter-fragmental porosity occur throughout. This "zone" occurs outside the Swan Hills Member but within the "Virginia Hills Member". In this paper it will be referred to as the "Coquina Zone". This "zone" may possibly be what Klovan (1964) calls an "in-situ accumulation without relief". The Imperial Goose River 12-23-67-18W5M well is solely producing from this "zone", and the B.A. Goose River 4-3-67-18 well is apparently obtaining production here, as well as within the Swan Hills Member. A detailed study of this "zone" was beyond the scope of this investigation.

GEOMETRY AND PALEOTOPOGRAPHY OF THE REEF COMPLEX

Drilling within the Goose River field and numerous off-reef tests have been carried out to the extent that the biohermal reef complex (Light Brown Submember) can be outlined fairly accurately (Figure 5) from the surrounding reefal platform (Dark Brown Submember). Because the drilling program has been carried out on a 320-acre spacing, only a general picture of the reef geometry and paleotopography can be made. More closely spaced control points are required to show detail of the reef structure. Only larger geomorphological features can be established such as lagoon, reef rim and slopes. Because of the scale of map used and number of control points, the writer felt that twenty-foot contour intervals were adequate (isopachous map of Dark Brown Submember has contour interval of ten feet). Link (1951) made an interesting statement regarding a geometrical and paleotopographical study of a reef when he said, "geologists attempting to contour reefs should consider how and into what forms they grew and to what geological processes the reefs were subjected before being buried by later sediments". Reef development will be discussed in a later section of this manuscript.

The following maps and cross-sections were constructed to illustrate the geometry and paleotopography of the Goose River biohermal reef complex. Each will be discussed separately:

(1) Structure contours on restored top of Swan Hills Member,

(2) Isopachous map of the Swan Hills Member (Light Brown and Dark Brown Submembers),

(3) Isopachous map of the Dark Brown Submember, and

(4) Two cross-sections through the reef.

1. <u>Structure Contours on Restored Top of Swan Hills Member</u>:

It is of interest to note that Link (1951) suggests that "a contour map on reef is erroneously referred to as a structure contour map" and that, "a reef is more a problem of morphology and it is suggested that a contour map of a reef or bioherm by termed a "morpho" contour map". This may be true, but because of long familiarity with the term structure contour map, the writer adheres to this terminology.

The present regional dip was removed in order to see the paleotopographic features in their proper relationships at the time prior to tilting in the so-called Alberta Syncline (an unrestored structural map was also constructed for comparison). The regional dip in the area is about forty feet per mile in a south, sixty degrees west direction. This was arrived at by estimating the regional dip and strike from the structure contours on the base of the Swan Hills Member. The structure contours on the restored top of the Swan Hills Member were arrived at by rotating each well control point about a datum line (which is the strike of the base of the Swan Hills Member) to a horizontal position and then contouring about these points (Figure 5). It was assumed that the initial dip was negligible or very small for as Klovan (1964) states, "it would be difficult to estimate the value of initial dip. Differential compaction within the complex affected the original topography but the amount of compaction is also difficult to evaluate". The stylolitic nature

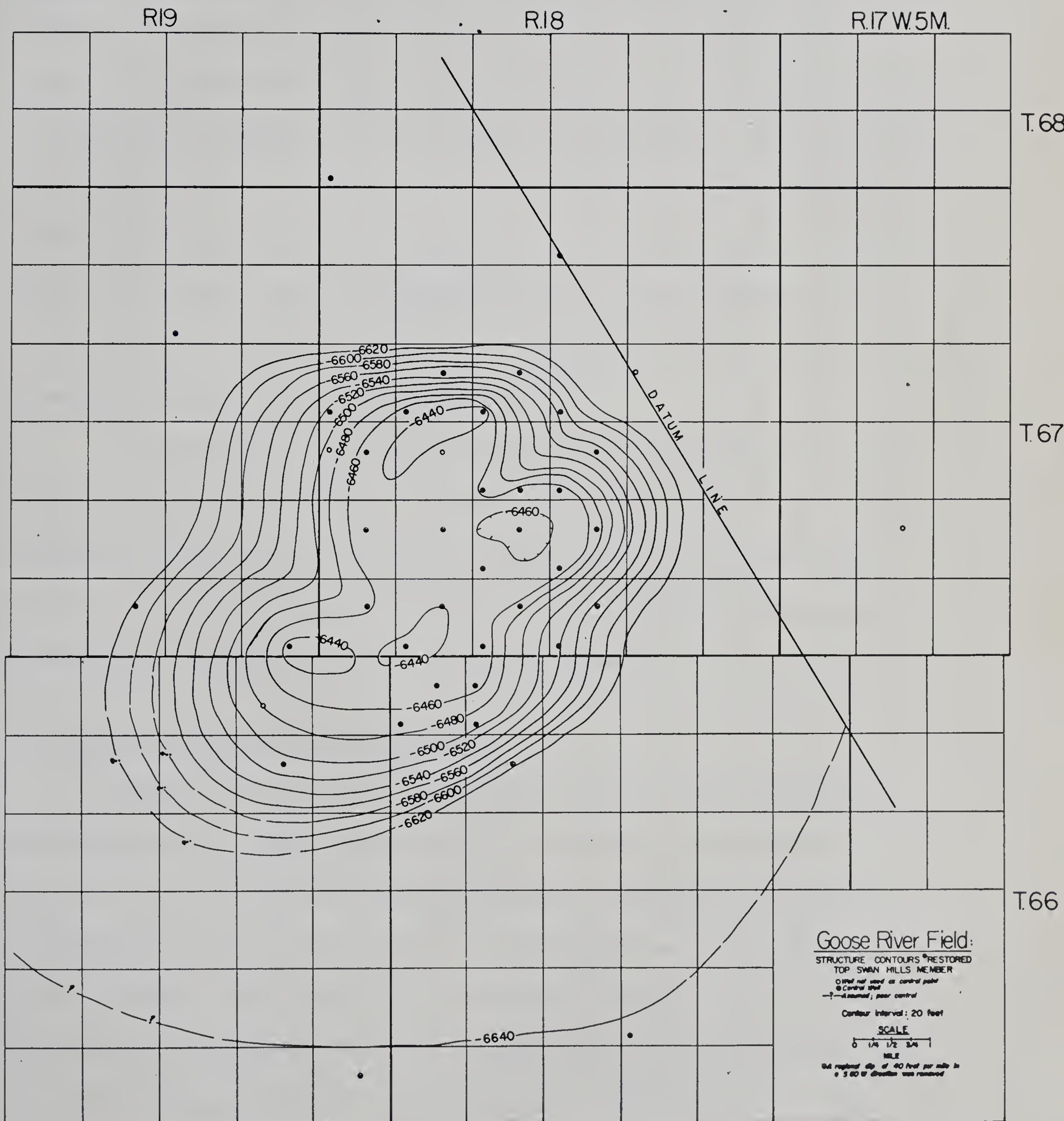

R19
R18
R17 W.5M.
T.68
T.67
T.66
DATUM LINE
-6620
-6600
-6580
-6560
-6540
-6520
-6500
-6480
-6460
-6440
-6640
Goose River Field:
STRUCTURE CONTOURS RESTORED
TOP SWAN HILLS MEMBER
Contour Interval: 20 feet
SCALE
0 1/4 1/2 3/4 1

Figure 5.

of the Swan Hills Member in the Goose River field allows a minimal compaction value to be worked out.

The map shows fairly steep slopes on most sides of the biohermal reef complex, and particularly on the north and south extremities. Towards the extreme southwestern part, where control is lacking, the slope may be more gentle. A plateau-like area occupies the interior part of the reef and is interrupted by three local highs and a depression. A low area exists around the B.A. 10-9 well which may have been due to an elevated rim to the immediate north. The highest part of the reef is located in the southwest portion, in the vicinity of the I.O.E. 2-1 and B.A. 4-5 wells. The reef complex has an oblong shape which trends in a southwest-northeast direction. No pronounced draping of overlying strata was observed from mechanical log investigations.

Three prominent re-entrants are evident; one in the northeast, a second in the southeast and a third in the northwest portion of the reef. These re-entrants probably represent channels between the lagoonal portion of the reef and the deeper open water to the east and northeast. They probably were responsible for bringing in nutrients for growth of local patch reefs.

2. Isopachous Map of Swan Hills Member:

Because a large number of the wells have not penetrated deeper than the base of the Swan Hills Member (and this is due mainly to the fact that the oil reservoir is located in the Light Brown Submember), control points for contouring an isopachous map (Figure 6) of the Swan Hills Member are not adequate for a detailed picture. The thickest section of Swan Hills Member, which coincides with the crest of the reef, is found in the western part of the reef complex, near the I.O.E. 201 well, where it attains a thickness of 300 feet. Klovan (1964) also found the crest of the Redwater Leduc reef to be located in the western portion of the reef complex. There is a difference of about 50 feet in elevation

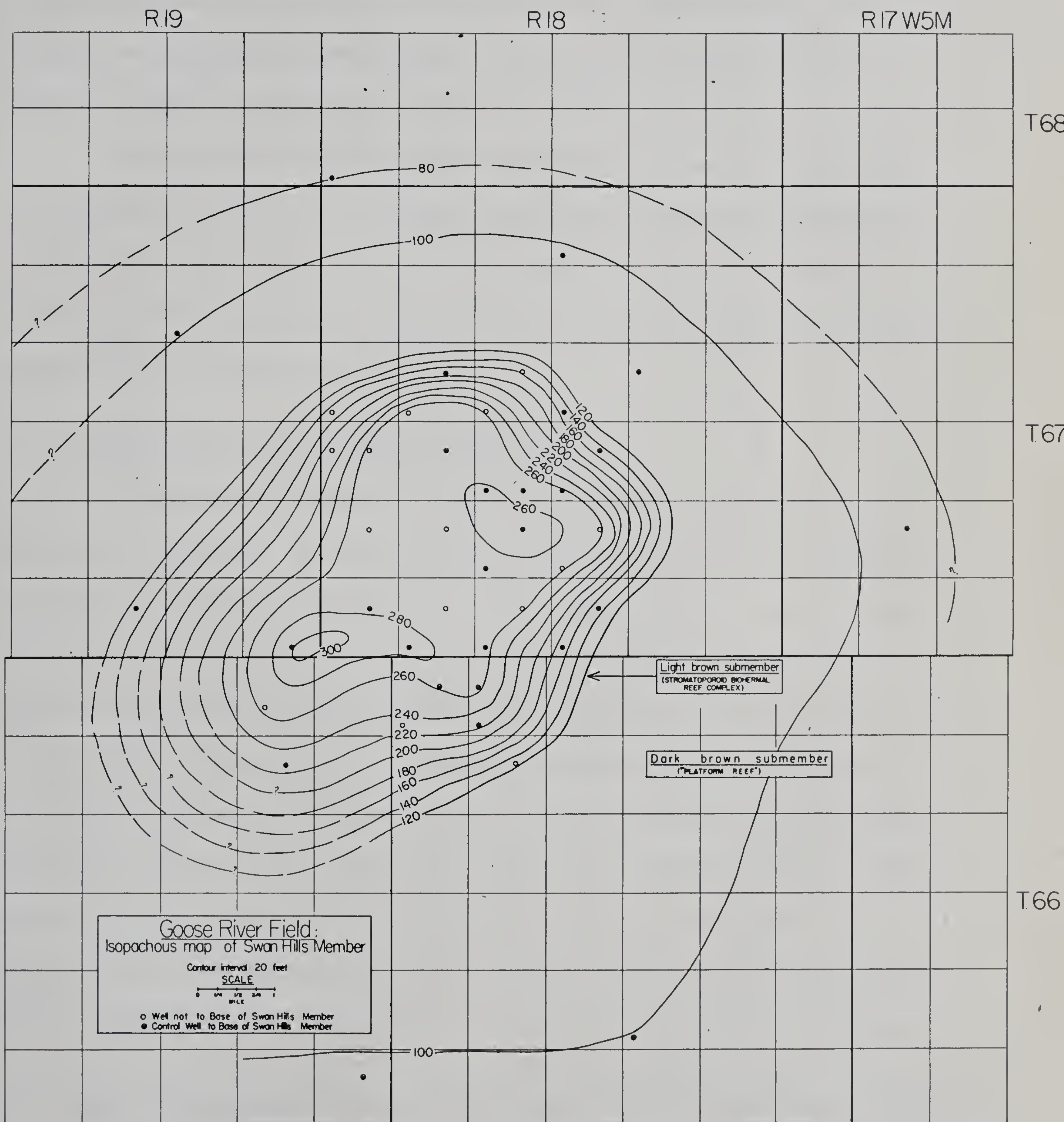

R19
R18
R17 W5M
T68
T67
T66
80
100
120
140
160
180
200
220
240
260
280
300
Light brown submember
(STROMATOPOROID BIOHERMAL REEF COMPLEX)
Dark brown submember
("PLATFORM REEF")
Goose River Field:
Isopachous map of Swan Hills Member
Contour interval 20 feet
SCALE
MILE
Well not to Base of Swan Hills Member
Control Well to Base of Swan Hills Member

Figure 6.

between the highest part of the reef (I.O.E. 2-1 well) and lowest part of the reef (near the B.A. 10-9 well). This map is similar in appearance to the restored-structure contour map on the Swan Hills Member. The map indicates how the Light Brown Submember (stromatoporoid, biohermal reef complex) stands out from the neighbouring Dark Brown Submember (platform reef).

An isopachous map of the Light Brown Submember was also constructed, but because of the difficulty in choosing the boundary between the Light Brown and Dark Brown Submembers (in core and on mechanical logs) it was felt that this map would not be as accurate as an isopachous map of the Swan Hills Member despite a lack of control points.

3. Isopachous Map of the Dark Brown Submember:

This map (Figure 7) has the same control points as the isopachous map of the Swan Hills Member. It was constructed to show possible loci for the initiation of Light Brown biohermal reef build-up. Water depth, salinity, currents, supply of nutrients, etc. are usually considered as requirements for favourable reef growth, but possibly also some topographic high is required. Because of the uncertainty in choosing the top of the Dark Brown Submember from core and mechanical logs (because of interfingering of Light Brown and Dark Brown facies), the map is subject to error. The highest isopach values (120 and 130) are located in the vicinities of the I.O.E. 201, B.A. 4-9 and I.O.E. 4-15 wells. The highest value is located near the I.O.E. 2-1 well, which is where the reef crest is found. These three areas are suggested as being loci for Light Brown reef growth.

4. Cross-Sections Showing Paleotopography (Datum-Top of Beaverhill Lake Formation)

Two cross-sections were drawn through the reef; namely, a southwest-northeast section and a northwest-southeast section (Figure 8). Because of wide well spacing and the small size of the reef body, geomorphic features of the reef

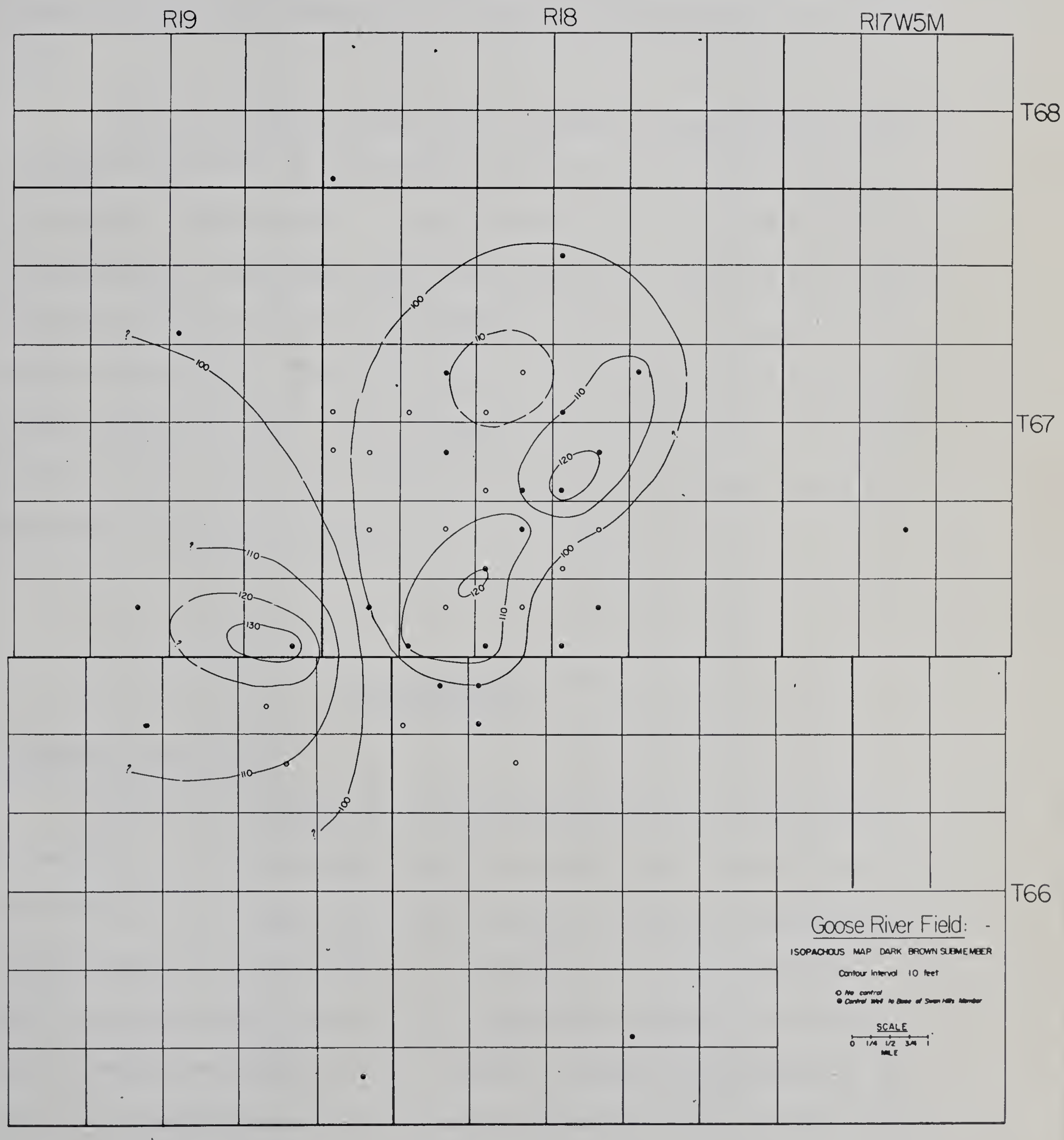

R19
R18
R17W5M
T68
T67
T66
100
110
120
130
Goose River Field:
ISOPACHOUS MAP DARK BROWN SUBMEMBER
Contour Interval 10 feet
No control
Control Well to Base of Swan Hills Member
SCALE
0 1/4 1/2 3/4 1
MILE

Figure 7.

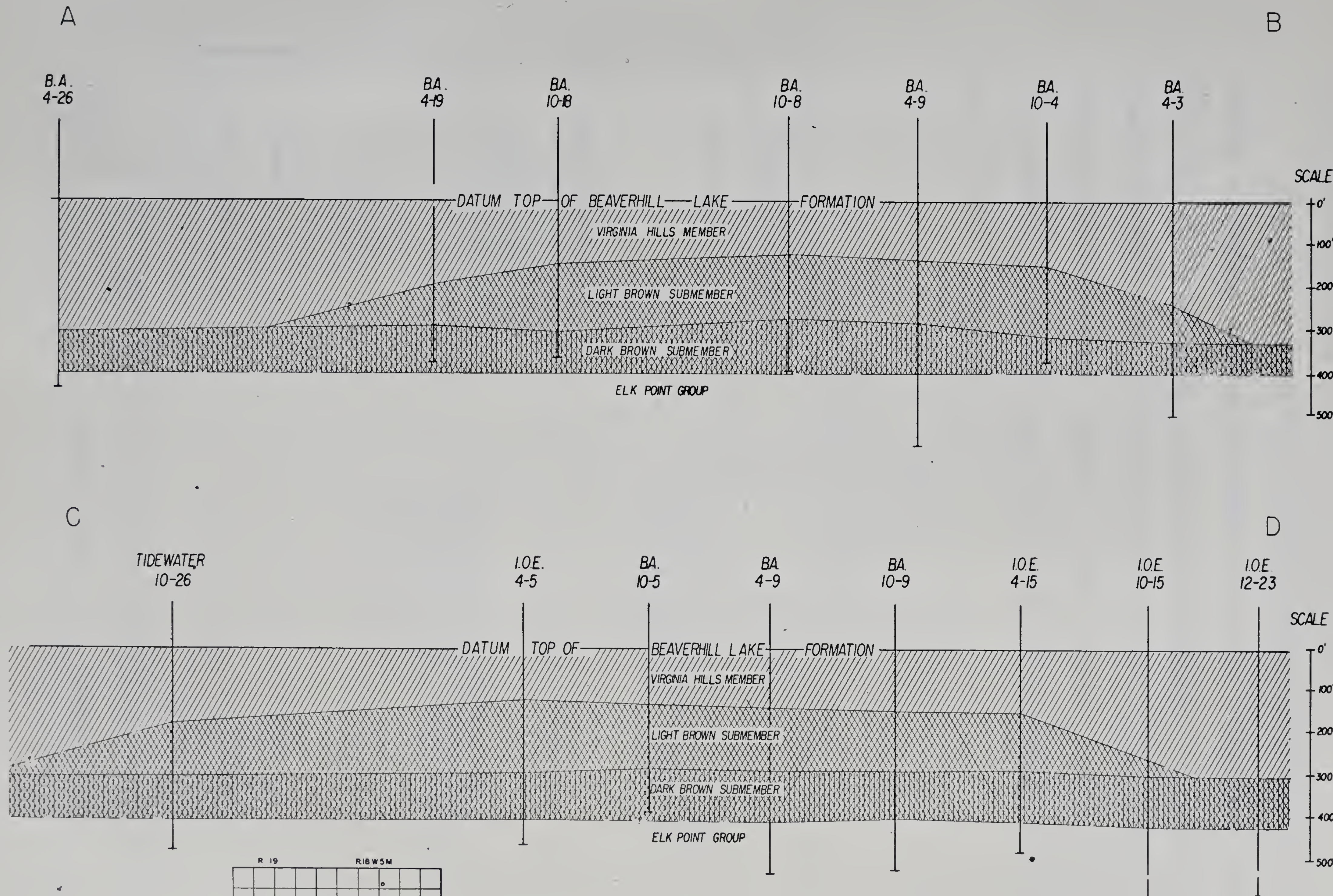
are not obvious but,a back-slope, crest, and outer slope are recognized. Fairly gentle outer slopes are apparent, (vertical exaggeration is thirteen and one half times). The crest of the reef complex is located in the western part (as indicated by section C-D). Also recognized is a plateau-like region near the B.A. 10-9 well.

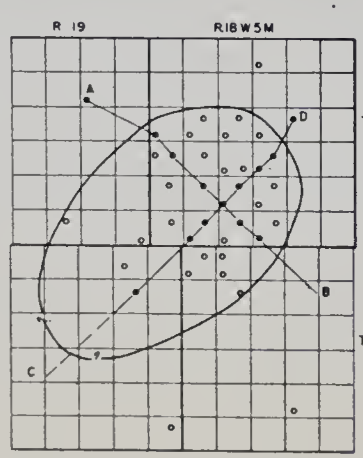
Link (1951) made the remark that, "The detailed shape and trend of reefs or bioherms appear to be as unpredictable as their composition and the porosity within them". And also that " .... some are linear like the Great Barrier Reef of Australia and Florida Keyes, some, like the Permian of West Texas area, have a fore-reef and back-reef facies quite different; some clusters or groups have no particular shape like the Bahamas; and many are isolated affairs which seem to follow no pattern whatever". This is probably true of ancient reefs as well. For example, the Swan Hills reef is different from the Kaybob reef which in turn is different from the Goose River reef.

PETROGRAPHY

Carbonate Classification

Carbonate petrography has evolved considerably within the last fifteen to twenty years, and this has been mainly due to the economic interest in these rocks which has in turn engendered studies in present day carbonate sedimentation. As a result textural, paleontological, environmental, and energy studies have added to the terminology, description and classification of these rocks (for historical review see Ham and Pray, 1962). However, as Baars (1963) pointed out, the symposium "Classification of Carbonate Rocks", published by the A.A.P.G. (1962), is a testimonial to the classification difficulties encountered by carbonate petrographers. Hence it appears that every carbonate petrographer modifies existing





STRATIGRAPHIC CROSS-SECTIONS THROUGH GOOSE RIVER REEF COMPLEX

SCALE:
Horizontal: = 4" = 1 mile
Vertical: 1" = 100 feet
Vertical Exaggeration: 13·5 times

Figure 8.

classifications somewhat to suit his own particular study.

In this study the writer has adopted the textural components (see Table 3) proposed by Leighton and Pendexter (1962) with emphasis placed on the grain/micrite ratio. Pre-existing terminology is used as much as possible. For example, the terms sparite (Folk, 1959), skeletal calcarenite, biocalcirudite and limestone-pebble conglomerate are used. Because of subtle distinctions between facies, the writer has found it necessary to apply rather long rock names (e.g. dark brown micritic-crinoid-brachiopod limestone).

TABLE 3

TEXTURAL COMPONENTS

Textural Component	Examples
1. Lime mud	upper size limit set at 0.03 mm.. referred to as micrite (Folk, 1959), ooze, lithographic, cryptocrystalline, or matrix
2. Grain types (5)	
(a) skeletal (fragmental and non-fragmental)	crinoidal, algal, stromatoporoidal
(b) non-skeletal (4)	
i. pellets	fecal pellets; micrite grains
ii. coated grains	oolites and superficial oolites; pisolites; algal or foraminiferal-encrusted grains
iii. lumps	composite grains; algal lumps
iv. detrital grains	rock fragments; intraclasts
3. Cement	usually sparry calcite
4. Pore space	organic, intergranular, vuggy

In-situ organic accumulation and recrystallized calcite are also considered as two other important textural components of carbonate rocks.

Particle Size Classification

The carbonate particle size classification adopted in this study is shown in Table 4. The writer felt that within the calcarenite size range it would be desirable to differentiate between fine, medium and coarse calcarenites when describing the rocks, but when it came to differentiating facies within the reef it was impractical to do this, and hence calcarenites were grouped together.

TABLE 4

GRAIN SIZE CLASSIFICATION

SIZE RANGE	DESCRIPTIVE TERM	
>2 mm.	Calcirudite	
2 - 0.6 mm.	CALC-ARENITE	Coarse Calcarenite
0.6 - 0.2 mm.		Medium Calcarenite
0.2 - 0.06 mm.		Fine Calcarenite
0.06 - 0.03 mm.	Calcisiltite	
< 0.03 mm.	Calcilutite (lime mud)	

Discussion of Textural Components and Diagenesis of the Facies in the Goose River Field

A discussion of the various textural components and diagenesis of the Swan Hills Member in the Goose River field follows, and the general distribution of these components is shown in Figure 9. The Swan Hills Member in the Goose River field will be referred to as the Goose River facies in this discussion.

1. Lime Mud - The lime mud component is a very fine-grained ooze with an upper size limit set at 0.03 mm. (after Leighton and Pendexter, 1962). It was termed micrite by Folk (1959) who set the upper size limit at 0.06 mm. Probably this upper size limit is not very critical. Such terms as microcrystalline calcite

ooze, cryptocrystalline limestone and lithographic limestone are also used to describe this dense, very fine-grained material. The term matrix is also used by some carbonate workers when referring to lime mud.

The origin of lime mud is still in some question. Folk (1959) conceived micrite as forming by " .... rather rapid chemical precipitation in sea water, settling to the bottom and in some cases suffering some later drifting around by weak currents". He further stated that "it may occasionally form in-situ" and may be "partly produced by inorganic causes (heating, evaporation, or agitation) and partly precipitated by algae, bacteria or other organisms". Folk and other workers have also suggested that lime mud may have formed from abrasion of larger skeletal material, with the result that this pre-existing material is broken down into clay or silt size material. Probably several mechanisms operate to produce material of this size.

The Goose River facies exhibit a high percentage of lime mud throughout. It varies in colour from cream to buff to medium-dark brown, is subtranslucent in thin section and is dense, dull looking in hand specimen. It occurs very commonly in the lagoonal portion of the Light Brown Submember and is a very common constituent in the Dark Brown Submember in skeletal calcarenites, pellet-intraclast micrites and dismicrite rock types. At times it is found as infilling of cells in stromatoporoids and Amphipora. Lime mud is the dominant constituent of pellets and intraclasts. As the amount of grain types, pore space and cement increase, there is a corresponding decrease in the amount of lime mud. It has also been observed in mud-supported rocks that rounding and sorting are not as well developed as in rocks with considerable sparry calcite. As Folk (1959), Klovan (1964) and numerous other workers have stated, presence of lime mud is indicative of very mild energy conditions and hence evidence for lack of turbulence. Lime mud was rare to absent in the Light Brown Submember at the I.O.E. 10-15, a fore-reef

well, where energy conditions were presumably turbulent in nature. Klovan (personal communication) points out that an absence of lime mud may be due to either turbulence or to a lack of lime mud. Lime mud appears to be rather susceptible to recrystallization.

2. Grain Types

(a) skeletal particles - Skeletal particles are the whole or fragmental remains of hard parts of various taxa. Skeletal grains include crinoidal debris, brachiopod grains, algal remains, *Amphipora* fragments, stromatoporoid grains, coral fragments, bryozoan fragments, and fragments of other taxa. The term skeletal grains also includes whole forms such as ostracods, foraminiferal tests, and calcispheres that have been deposited as sediment. The framebuilders such as stromatoporoids, *Amphipora*, corals, etc. will be discussed in a separate section later.

Skeletal grains are recognized by their similarity in appearance to larger, whole neighbouring fossils, by micro-structure (if not recrystallized) and are lighter in colour than the surrounding groundmass. Skeletal grains (fragmental) are usually interpreted to be the result of some form of physical action such as currents and pounding surf. Possibly biological processes are also important in breaking down shells.

Skeletal particles occur commonly throughout the Goose River facies and usually range from fine to coarse calcarenite in size. Their occurrence is well noted in the lagoonal area of the biohermal reef complex where they are associated with lime mud and tend to be finer size. The degree of sorting and roundness of these grains varies, depending upon environmental energy conditions.

(b) non-skeletal particles

(i) pellets - Following Folk (1959, p. 6) pellets are defined as "rounded,

spherical to elliptical or ovoid aggregates of microcrystalline calcite ooze, devoid of any internal structure". They range in size from coarse silt to fine sand. Pellets can be the end result of various processes or origin. Folk said, "they probably represent fecal pellets of worms or other invertebrates" and that "some form in places by a form of recrystallization". Illing (1954) suggested a non-biologic origin for some types of pellets, wherein mud-size sediments on the sea floor adhere to each other and become ovoid by a gentle rolling-about on the bottom due to moderate wave action. Probably both biologic and non-biologic kinds of pellets are found in the Goose River field.

Within the Swan Hills Member, pellets occur in ovoid to ill-defined shapes (with vague boundaries) ranging in size from silt to medium sand. They are best observed when surrounded by clear sparry calcite, as for example in some of the Dark Brown Submember facies. The pellets are usually light brown to medium brown in colour with the darker colour probably due to staining of bituminous matter. Generally the pellets are of homogenous composition, but some with thread-like borings through them were encountered. These dark brown twisted, thread-like borings may be algal in origin. Small, cluster-like groups seemed to be common mode of occurrence for the pellets. These clusters may form grain types called lumps. It was observed that pellets show some resistance to recrystallization, because where the lime mud has obviously undergone recrystallization, the pellets remain floating within this clear recrystallized calcite. Illing's (1954) studies of recent faecal pellets have shown that they are soft and friable. Hence he suggests that the scarceness of friable pellets indicates that their cementation is rapid. The writer found, as also did Klovan (1964), that pellets may become confused with intraclasts when their composition is the same. Thin-section study facilitates differentiation between the two, but if the grains are small it is difficult to make the distinction between the two; shape sometimes helps. Because of their

association with sparry calcite a moderately turbulent environment is suggested for their deposition.

(ii) coated grains - Grains having a concentric or enclosing layer of calcium carbonate around a central nucleus are called coated grains (Leighton and Pendexter, 1962). These include oolites, pisolites, and algae-encrusted or foraminifera encrusted skeletal grains. Oolites are physiochemically precipitated coated grains which show radial or concentric structure about a central nucleus. They form in a shallow, agitated water environment. Folk (1959) considers pisolites, which are usually oblong in shape, to be algal concretions and hence genetically different from oolites. The writer agrees with this interpretation. Regarding the algae-encrusted grains, Baars (1963, p. 107) states that from modern day studies "some types of blue-green algae are capable of coating the grains they live on" and that these "algal concretions seem to be most common in very shallow to intertidal marine environments".

There is an absence of oolites in the Goose River field which may be due, as Klovan (1964) suggests, to the sea water being unsaturated with calcium carbonate in the area at the time. Algal-coated grains and pisolites appear to be common in some of the Swan Hills facies associated with fair to well sorted intraclast-pellet sparite rock types. The so-called oncolites are algal-coated particles also, and range up to four centimetres in size. They are associated with the same rock type.

(iii) detrital particles - Leighton and Pendexter (1962) define detrital grains as those grains derived from pre-existing rocks. Because of their derivation from pre-existing rocks they can be either intrabasinal, to which Folk (1959) attaches the name intraclasts, or extrabasinal (or terrigenous). It is often difficult to tell whether these detrital grains are intrabasinal or extrabasinal in ancient limestones. The writer believes that most of these particles that are present in the Goose River field have originated from "weakly consolidated penecontemporaneous carbonate

sediments that have been torn up and re-deposited by currents within the basin" (Folk, 1959, p. 4), and hence they are termed intraclasts. These intraclasts can be essentially composed of one rock type (oligomictic) or of several rock types (polymictic). Intraclasts probably suggest a shallow water, intertidal environment with some exposure and dessication. Terrigenous grains are probably present in the shaly breaks within the reef complex. For example, Carozzi (1961) states, "that detrital minerals are absent in the reef environment, but some angular grains of detrital quartz are found in the shale breaks.

Within the rocks studied, the intraclasts occur as sub-rounded to rounded particles ranging in size from fine sand to pebbles. They are usually oligomictic, being composed of micrite, but may be polymictic, having a skeletal or other grain type surrounded by micrite. They are of common occurrence in the Goose River field, and as was mentioned previously, can be confused with pellets.

(iv) lumps - These are composite grains that are bound together by some process of cementation. They are believed to have formed by a process of aggregation. Illing (1954, p. 29) says that, "the various habits assumed by these lumps are typical of certain environmental conditions" and he recognizes such forms as grapestone, botryoidal lumps, encrusted lumps and others.

In the Goose River area lumps usually occur as clusters of pellets and/or ill-defined micrite grains (intraclasts?) surrounded by sparry calcite cement. They occur fairly commonly in pelleted-intraclast dismicrites and pelleted-micrite limestone rock types. The writer suggests that probably some of these lumps are actually differentially recrystallized lime mud, and hence are of a secondary origin.

3. Cement

This is the clear crystalline component that fills the spaces between grains. In limestones the cement is usually sparry calcite and/or dolomite. Referring to

sparry calcite cement Folk (1959) states that, "this type of calcite usually occurs as a simple pore-filling cement precipitated in place .... (and) sometimes formed by recrystallization of finer carbonate grains". The writer found both types of occurrences in the Swan Hills Member. Sparry calcite is distinguished from lime mud (microcrystalline calcite) by its clarity and coarser crystal size. Where sparry calcite occurs in laminite and dismicrite rock types or as filling of cells in fossils (for example, the axial canal and marginal vessicles in Amphipora) the writer believes it to be formed by precipitation in place. The formation of sparry calcite by recrystallization of lime mud is also evident where boundaries are irregular and when pellets are freely floating within it.

Sparry calcite as defined by Folk is that "calcite which has been deposited from solution on a free surface". Recrystallized calcite, on the other hand, is that calcite that has occupied its present space by replacing another mineral or assuming a different form of the same mineral (Stauffer, 1962, p. 362). The reader is referred to Bathurst (1958) and Stauffer (1962) for further discussion on the subject with regards to differentiating between the two.

Dolomite is usually formed by secondary replacement and hence will be discussed under diagenesis, following the discussion on pore space.

4. Pore Space

Pore space, which is probably the most important of the textural components from the standpoint of oil occurrence, depends upon the interrelationships of all the foregoing textural components; namely, the amount of lime mud, amount of cement, and the size, shape, roundness, sorting, and packing of grains. Porosity will also be affected by diagenesis, stylolitic solution, and amount of argillaceous material. For further discussion on porosity in carbonate rocks, the reader is referred to the excellent papers of Murray (1960), Thomas and Rhodes (1961), and Thomas (1962).

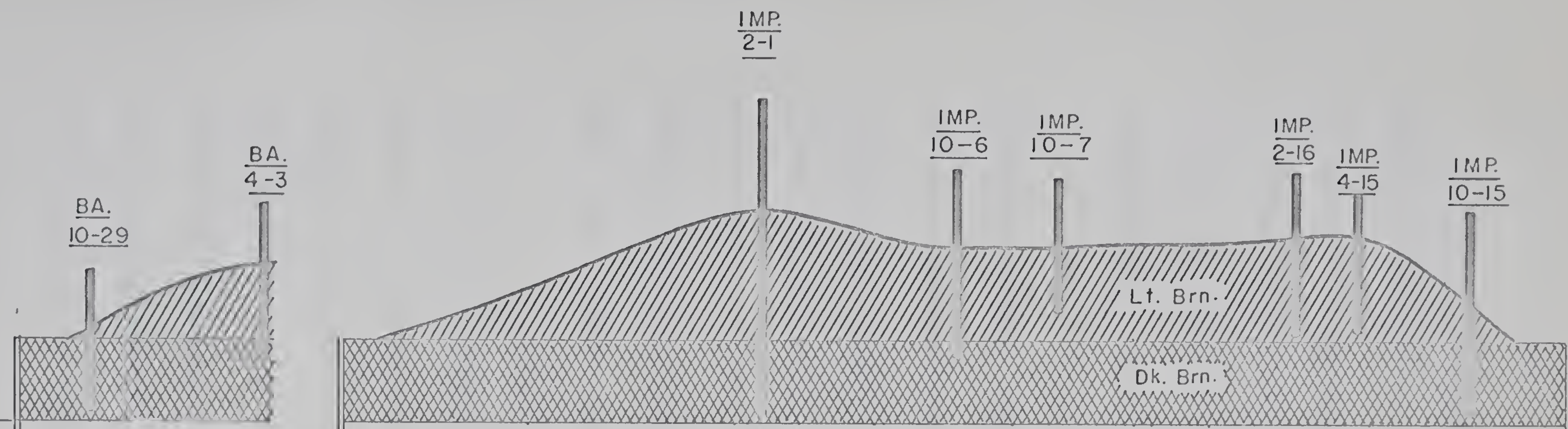
The porosity in the Goose River field is mainly confined to the Light Brown

Submember where it occurs dominantly as intraorganic and intergranular pore space. Thin, discontinuous lateral and vertical streaks of porosity occur in the Dark Brown Submember, with the best development in the so-called "Coral Zone" (which is poorly developed in the Goose River area). Within the "Virginia Hills Member" a laterally discontinuous "Coquina Zone" (about twenty feet thick) has thin bands of interfragmental porosity.

The best development of porosity is located in a boomerang shaped area along the north, east and south parts of the field within the Light Brown Submember. Edie (1961, p. 448) also mentions that within the Swan Hills field, "in general greater proportion of dark brown and light buff impermeable precipitated limestone is present in the central portion of the reef mass, whereas permeable types are concentrated near the reef margins". It is here that the energy conditions would be highest, resulting in medium to coarse biorudites with small amounts of matrix and very little cement and no accumulation of finer material; the end result being well developed porosity. Its vertical continuity is interrupted by dense zones of micrite limestones and where stromatoporoids and Amphipora are infilled with sparry calcite. Because of the lenticular nature of the porous zones it is difficult to trace them laterally. Generally oil stains or solid bitumen are located in the pore space. Fractures do not appear to contribute very greatly to the overall porosity, and are generally filled by a secondary mineral such as dolomite or anhydrite.

DIAGENESIS

Diagenesis is commonly defined as post-depositional and pre-lithification changes occurring in a sediment (Powers, 1962). Two diagenetic processes will be discussed as they occur in the Goose River field; namely, authigenic changes (caused by reaction between the sediment and intrastratal solutions), and compaction,



			BA. 10-29	BA. 4-3	IMP. 2-1	IMP. 10-6	IMP. 10-7	IMP. 2-16	IMP. 4-15	IMP. 10-15
LIME MUD				XX	XX OO	XXX	XXX	XX	XX	X OOO
GRAINS	SKELETAL		X	XX	XX	XX	XX	XXX	XXX	XX
GRAINS	NON-SKELETAL	PELLETS	X	X	X OO	XX	XX	X	X	OOO
GRAINS	NON-SKELETAL	COATED GRAINS	XX	X	X O	X	X			X O
GRAINS	NON-SKELETAL	DETRITAL and INTRACLASTS	XX	X	XX O	X	X	X	X	X O
GRAINS	NON-SKELETAL	COMPOSITE		X	X OO	X	X			OO
PORE SPACE			X	X	XX O	X	X	XXX	XXX	O
AUTHIGENIC MINERALS	SPARRY CALCITE CEMENT		XXX	X-XX	XX OOO	X-XX	X-XX	X-XX	X-XX	X-XX OOO
AUTHIGENIC MINERALS	RECRYSTALLIZED CALCITE			XX	X OO	XX	XX		X	OO
AUTHIGENIC MINERALS	DOLOMITE REPLACEMENT				X	X		X	XX	XX OO
AUTHIGENIC MINERALS	ANHYDRITE				O					O
AUTHIGENIC MINERALS	SILICIFICATION				X O					XX O

DISTRIBUTION OF TEXTURAL COMPONENTS IN THE GOOSE RIVER REEF COMPLEX

Figure 9.

Light Brown Submember		Dark Brown Submember
X	RARE	O
XX	COMMON	OO
XXX	ABUNDANT	OOO

which is best shown by presence of stylolites.

1. Authigenic Changes - Rock textures can be altered by numerous generations or stages of authigenesis. Powers (1962) in his study of Arabian Upper Jurassic carbonate reservoir rocks recognized six different stages of authigenesis; namely, (1) addition of a drusy calcite coat around calcarenite particles, (2) recrystallization to mosaic calcite, (3) cementation by clear calcite, (4) growth of anhydrite crystals, (5) dolomitization, and (6) silicification.

The writer has observed the above-mentioned stages to varying degrees in the Goose River field. Sparry calcite cement and recrystallized calcite have already been mentioned under the discussion of cement, so they will not be discussed further except to mention that within numerous ostracod valves two generations of sparry calcite can be seen, and that sparry calcite occurs in geopetal relationship with lime mud within brachiopod shells. In some of the more porous calcarenites, grains show a drusy coating of calcite crystals. Dolomite replacement occurs rather commonly in large irregular vugs in some of the rocks, and also as fine to medium dolomite rhombs in the matrix of biorudites. The I.O.E. 10-15 rim well commonly shows partial silica replacement of cells in massive and laminar stromatoporoids. The silica replacement has the appearance of minute euhedral to anhedral shaped crystals. It is suggested that the silica replacement may represent a brief period of uplift and exposure to weathering or that the pH of the marine waters may have been low. Galloway (1957) stated that weathering makes stromatoporoids susceptible to silicification. Anhydrite is not very common in the Light Brown Submember as a replacement mineral, but does occur in irregular shaped vugs and fractures. The relative times of the foregoing authigenetic processes have not been worked out.

2. Stylolites - Twenhofel (1960) defined stylolites as "vertically striated columns, pyramids, and cones of various heights, widths and shapes on bedding planes and

less commonly on planes of other origin". Other names synonomous with stylolites are epsomites, crystallites and crawfeet. There are two main, opposing hypotheses on the origin of stylolites; that is, whether they are primary or secondary. The former is called the "contraction-pressure theory" (originally proposed by Marsh, 1867 and today strongly supported by Shaub, 1939, 1947, 1949, 1953) in which stylolites are believed to be a "primary structure which originated while the sediments were in the unconsolidated state from differential pressure and contraction which compelled transfer of material by plastic flow". Stockdale (1922, 1926, 1943) on the other hand strongly supports the later idea called the "pressure-solution theory" (originally proposed by Wagner, 1913) in which stylolites are a secondary phenomenon developed after consolidation and hardening of strata through rock removal by differential chemical solutions. The pressure is due to the load of the overlying sediments or tectonic forces. To sum the argument up, Shaub believes that there is no removal of material, while Stockdale believes that there is removal of rock substance. Prokopovich (1952), after studying stylolitic carbonates in Germany, came to the conclusion that stylolites form by solution in soft sediments, and he uses an explanation of variable pH in water to account for this.

Probably Stockdales' explanation for stylolite formation is the most widely accepted and is the basis for the study made by the writer, but as Prokopovich (1952) points out .... "it is probable that stylolites originated in many ways".

Stylolites observed within the Goose River reef complex (see Plate I) are variable in size and shape, and also in colour, composition and thickness of the material which constitutes the stylolitic seams. Ranging in size from microscopic (between individual penetrating grains) to macroscopic (with relief up to two inches in places), the stylolites appear as fine sutures to striated and polished stylolitic columns. The colour of the material in the seams varies from light to medium brown

in the smaller, hair-line stylolites, to dark brown to black in the larger ones. Twenhofel (1950) suggests, "thickness (of seams) seems related to quantity of insoluble residue in the rock penetrated by the elevations and to the extent of penetration". The insoluble material appears to be of a bituminous-argillaceous-organic nature, and is thickest at the summits and depressions of the stylolitic seam. In places pyrite subes are common along the seams, and, where seams bifurcate carbonate fragments are enclosed. The stylolites occur mainly in a horizontal to sub-horizontal orientation, but they do occur obliquely and very rarely vertically.

Some carbonate facies are not as stylolitic as others. For example, a pellet-skeletal micrite facies with eyes of spar has few associated stylolites, while an Amphipora facies has numerous stylolites throughout. Stylolites have also been observed to occur at contacts of different rock types. They occur rarely within a uniform, virtually unfossilliferous rock type, but microstylolites are common between grains and individual fossils. Some of the thicker black, shaly accumulations probably represent hiatuses within the reef.

In the immediate vicinity of some stylolitic seams there are found dolomite rhombs and pyrite cubes and, to either side of the seam, the sparry calcite infilling of fossils has been replaced by dolomite in part. It is suggested that a possible source of silica for the silica replacement in tabular stromatoporoids could be from nearby stylolites.

According to Stockdale (1926) a minimum reduction in thickness of rocks by pressure-solution can be calculated by using either the stylolite heights or solution residue and he further stated that a reduction of thickness of as high as forty percent has been calculated. The writer attempted to calculate a minimum reduction of thickness for a particular interval of core in the B.A. 4-3 well by measuring only the macro-stylolites using calipers. The following figures were obtained:

Thickness of core section measured	448.25"
Number of macro-stylolites measured	86
Estimation of minimum loss of material by solution	45.36"
Therefore, minimum original thickness	493.61"
Approximate minimum loss	9.2%

If there actually is a loss of material due to the formation of stylolites as Stockdale suggests, then any hydrocarbons (oil) present at the time would have to be expelled from one part of the carbonate rock to another. Hence, stylolites will affect the reservoir characteristics of the rock. Such things as cementation, texture, and rock competency will also change. As a result further studies on stylolites might yield important information with respect to reservoir characteristics.

FOSSILS: TYPES, DISTRIBUTION AND ECOLOGY

Included in this discussion are the whole (micro and macro) and the partly fragmental macrofossils; highly abraded fossils are not included. For example, microfossils such as calcispheres and ostracods are discussed as are the large stromatoporoids. Identification of most fossils has been done only on a general basis - no species were identified. Stromatoporoids were by far the most abundant fossils in the Goose River reef complex and they have been subdivided into three categories; namely, massive, tabular, and dendroid or branching.

Most of the fossils studied are virtually in-place accumulations (transportion, if any, occurred over a very short distance only, for abrasion of fossils is not very apparent). Fossils in original position of growth are difficult to see, and only in rare circumstances were they interpreted as such. Following Nelson, et al. (1962, p. 235-237), criteria which are suggestive of in-place accumulations are:

(1) growth habit of organisms - if growth habit is known (and this is not definitely known with regards to stromatoporoids) then occurrence of organism in position of growth is evidence of accumulation in place.

(2) faunal zonation - is indicative of biological activity, not a result of physical processes of accumulation. Fishbuch (1962) illustrates this with stromatoporoids in the Kaybob reef.

(3) distribution of shells of solitary organisms - a large deposit of complete shells suggests accumulation in place.

(4) lithologic evidence - a deposit of relatively whole unabraded shell material suggests accumulation in place.

(5) structural evidence - in-place accumulations may have a bedded structure; beds dipping away from the main deposit indicate that the framework actually stood above the surrounding sediments.

A discussion of the fossils encountered in the Goose River reef complex will now be undertaken. Figure 10 shows a general distribution of organisms throughout the reef complex.

Stromatoporoids

Stromatoporoids are benthonic, sessile marine organisms found mainly in biohermal or biostromal reef limestones. Regarding stromatoporoids in general, Galloway (1957) states that they are indicative of a clear, warm, shallow water marine environment with annual change of seasons. Some stromatoporoid bioherms show that they could flourish in water only a few feet deep, and subject to the pounding of breakers, comparable to present-day organic reefs. According to Galloway, "the skeletons of stromatoporoids were originally constructed of calcium carbonate, apparently in the form of calcite, rather than that of aragonite, for there is little indication of change in the form of crystallization since the skeletons

were made".

<u>massive</u> - Massive stromatoporoids are hemi-spheroidal or dome shaped to ball or spherical in shape up to ten to fifteen centimetres in width. As Klovan (1964, p. 35) states, "probably the maximum size has not been observed in the cores". Most were fragmentary to some degree and as already mentioned above, it was difficult to tell with certainty if any were in original growth position. They are found in greatest number in the rim oil wells, towards the base of the Light Brown Submember and also, in part, within the Dark Brown Submember. Massive stromatoporoids are found at times associated with encrusting algae (stromatoporoid-algal consortium) and also encrusting other stromatoporoids. Associated fossils found with these massive stromatoporoids are brachiopods, branching stromatoporoids and also cup corals at times. Lecompte (1951) found that corals and stromatoporoids do not normally occur together in bioherms. In the Goose River reef complex the massive stromatoporoids do not appear to be as abundant as the tabular stromatoporoids and they are, in part, associated with them. According to Cloud (1952), massive stromatoporoids grew on a solid base and were resistant to the force of waves. They represent a high energy environment. Klovan (1964) agrees with Lecompte (1956) that massive stromatoporoids were adapted to turbulent water environments. The writer finds, as does Klovan (1964, p. 36), that massive stromatoporoids are also found in a black bituminous-argillaceous matrix which would not suggest turbulent water. As very little evidence for in-situ accumulation was found, these massive stromatoporoids were probably transported a short distance to a less agitated water environment. The ball-shaped stromatoporoids are probably indicative of a lower energy environment, because of their "solitary" habit (no colonies were found). Besides various energy levels influencing stromatoporoid growth, the supply of oxygen, nutrients, amount of suspended argillaceous material, etc., would affect their shape and size.

tabular - Tabular stromatoporoids are flat-laminar to slightly undulating in shape and attain thicknesses up to eight centimetres. They were found mainly in a horizontal position. Most were fragmentary and surrounded by a matrix of dark grey-black bituminous to argillaceous material with fine to coarse skeletal grains. Some were found in cleaner limestones. Brachiopods, crinoids (locally), and branching stromatoporoids are associated with them. Physiographically they are found in almost the same position within the reef as are massive stromatoporoids, except that the former are probably more common in deeper parts. This agrees with Klovan's (1964) observations. It has been suggested that they represent a medium energy level, with a fairly solid substratum to grow upon. Most of the tabular stromatoporoids observed in the Goose River reef complex are interpreted as having been transported a short distance from the site of growth (because of their fragmentary condition).

dendroid - The dendroid stromatoporoids are branch-like or finger-like in shape. They occur in great abundance in the Goose River reef complex. In this discussion they are subdivided into two groups; viz., branching (which includes Stachyodes) and the amphiporoids (Amphipora). Stachyodes, being bigger and stubbier shaped probably represent an agitated water environment, while Amphipora, which are somewhat more slender and delicate, are probably indicative of a quiet water environment.

Stachyodes and other branching stromatoporoids are found mainly in a fragmentary state, but in the I.O.E. 4-15 well they were interpreted as being in position of growth. The mode of growth and attachment are unknown, but Klovan (1964) suggested that they probably grew as bush-like colonies. Within the Light Brown Submember in the Goose River area, Stachyodes and other branching stromatoporoids occur in Fischbuch's (1962) inner and outer zones, while Amphipora occur in the so-called central or lagoonal zone. The distribution of the branching

stromatoporoids in the Goose River reef complex is of wider occurrence than that of the Kaybob reef, as delimited by Fischbuch (1962). Branching stromatoporoids and Stachyodes occur in association with large stromatoporoids and also with Amphipora to a lesser degree. Within the lagoonal portion of the reef complex, Stachyodes are of rare occurrence.

Towards the base of the Light Brown Submember Stachyodes and other branching stromatoporoids are usually very common and are generally associated with large stromatoporoids.

They are found associated with fine to coarse subrounded to rounded calcarenite grains and also with finer sediment. The writer agrees with Klovan's (1964) interpretation that they probably lived in a turbulent to moderately turbulent environment. In the I.O.E. 4-15 well, the writer observed a portion of the reefal core which to him suggested vertically branching Stachyodes in position of growth entrapping medium to coarse calcarenite grains.

Amphipora, which are finger shaped, occur very abundantly in the lagoonal portion of the Goose River reef complex. They are somewhat fragmentary and are found scattered in a particular facies or else concentrated in thin zones with practically no matrix. No branching types were seen and their mode of growth is uncertain. Most Amphipora were observed in a horizontal position and because of their unabraded appearance were interpreted as being in-situ or fairly close to their place of growth. Edie (1961) suggests that Amphipora thrived particularly along the inner portion of the organic attice.

The writer finds that Amphipora are generally associated with fine grained sediments and also with a somewhat argillaceous (?), bituminous lithology, especially in the Dark Brown Submember. Fischbuch (1960, p. 119) says that "Amphipora seem to be too widely tolerant to be useful as indicators of environment". They are found predominantly in the back-reef facies and throughout the Dark Brown Submember.

A few of the wells investigated showed a one to three foot development near the top of the Dark Brown Submember of pancake type Amphipora, fragmentary and usually in a horizontal position. Klovan (1964) called them "Euryamphipora". They are associated with a dark brown to black, bituminous matrix. Very little is known about them.

Stromatoporoid-Algal Consortium

These are nodular and dome-shaped encrusting fossil structures which were observed in the fore-reef I.O.E. 10-15 well and also in the I.O.E. 2-1 well. Klovan (1964) suggests that they indicate a moderately turbulent water environment.

Corals

Corals do not appear to occur very commonly in the Goose River reef complex except towards the base of the Swan Hills Member in a position equivalent to the "Coral Zone" in the Swan Hills area. Two varieties were observed; namely, a large solitary cup coral identified as the genus Tabulophyllum and, more commonly, the dendroid tabulate coral Thamnopora (probably the genus Coenites).

Corals prefer to live in an open, normal, marine water environment. Edie (1961) suggests that the dearth of corals in the lagoonal area is due to high salinity which they could not tolerate (while Amphipora could). Since Thamnopora in this study were found associated with large stromatoporoids, brachiopods, and other stromatoporoids, a deeper water environment is suggested. The large unabraded cup corals are of rare occurrence throughout the Light Brown Submember and were encountered in various facies.

Brachiopods

Whole brachiopods and single valves are common in some parts of the reef

complex where they are generally associated with crinoids, large stromatoporoids, and tabulate corals. The surrounding matrix is usually dark brown to black bituminous to argillaceous (?) material, with medium to coarse calcarenite grains. They range up to four centimetres in size and are mainly punctate varieties. Rim wells such as the I.O.E. 2-1, I.O.E. 10-15 and B.A. 4-3 wells show the commonest occurrences of brachiopods, most often towards the base of the Swan Hills Member. Sheltered grain effect and geopetal accumulation within brachiopods are a common phenomenon. Only the genus Atrypa was identified. Fischbuch (1962) recorded the presence of Atrypa at the base and outer edge of the Kaybob reef. The writer also observed Atrypa in the same positions.

Fragmental brachiopod valves are very common in the "Coquina Zone" of the "Virginia Hills Member", where they are interpreted as being part of a beach deposit.

Brachiopods are not considered reef builders, and different types may represent different environments. Edie (1961) says that "articulate brachiopods and crinoids are intolerant of the atoll-lagoonal area of reef where there was higher salinity prevailing". Within the Goose River lagoonal facies no crinoids or brachiopods were observed.

Echinoderms

Crinoids have already been mentioned to some extent in the above discussion of brachiopods. Because they are found in the fore-reef well and are associated with blackish, bituminous, argillaceous matrix, they probably represent a quiet, keep water marine environment (although crinoids are known to live in shallow water as well as very deep water). They are absent in the lagoonal area and generally in the Dark Brown Submember, except towards the base where they are associated with brachiopods. Their presence in a lime mud-dismicrite facies in the

B.A. 4-3 well suggests that they also dwelled in some sheltered environments on the reef.

Echinoid spines and crinoids are very common in the "Coquina Zone", where they probably represent part of a beach deposit.

Foraminifera

Forams are known to occupy various reefal environments. In the Florida Keyes area of low tides and moderately quiet waters, they are an important contributor to the carbonate deposits. Forams occur rarely in the Goose River reef complex, but the writer noticed a few uniserial types of organisms which are interpreted as forams, and some hollow tubes of doubtful identification in the lagoonal part of the reef. The uniserial form is identified as the genus Reophax, which is known to occur in the lagoonal portion of the reef. Some other forms were observed which are similar in appearance to calcispheres and are found in the lagoonal portion of the reef, but after reading Toomey's (1965) paper the writer has interpreted them as the foram Parathurammina. According to Toomey, "parathuramminids are restricted to the inner lagoonal area and occur in pelletoid wackestones, along with abundant calcispheres".

Ostracods

Ostracod shells (whole and single) have been observed mainly as minor constituents in the lagoonal portion of the reef where they occur in small clusters or else disseminated in a fine calcarenite-micrite rock type. They contribute to porosity at times (see also Beard, 1959). Ostracods are benthonic dwellers, but probably some tests floated to the surface and, as a result, they can be found almost anywhere within the reef complex. They represent a shallow water environment.

Mollusks

The writer did not observe any pelecypods or cephalopods in the Goose River field, but their presence has been recorded in other Beaverhill Lake reefs. Their recorded absence may be the result of core sampling. Gastropods are found in minor amounts throughout the reef. Klovan (1964) says that gastropods were tolerant of a wide range of environments.

Bryozoans

Bryozoans are rare to absent within the reef, but are abundant as fragmentary forms in the "Coquina Zone". They are tolerant of a wide range of environments.

Algae

Studies of modern reefs indicate that algae play an important part in carbonate sedimentation (see Lowenstam, 1955). In some ancient reefs their role is difficult to assess. Johnson and Konishi (1958) say that rock-building algae appear to be scarce and restricted in Devonian times. Cloud (1952, p. 2126) sums up the role of algae in carbonate sedimentation by saying, "the part played by calcareous algae in the formation of existing and ancient reefs is conspicuous to dominant". Algae indicate shallow water environment (generally depths of less than one hundred feet).

Algae do not appear to be important reef builders in the Goose River reef complex, but the following algae were observed in minor occurrences. Fragments of the genus Parachaetetes (a Solenoporacean algae) occur scattered throughout the reef. In the B.A. 10-29 well they are found associated in a fair to well sorted intraclast-sparite rock type. In other parts of the reef they are associated with biocalcirudites. Edie (1961) and Brown (1963) also observed in their studies in the Swan Hills field that Parachaetetes is found in skeletal calcirudites.

Girvanella, a porostromatacean algae, was observed in very minor amounts in pelleted to intraclast-micrite facies with eyes of sparry calcite. Brown (1963, p. 180) says that, "Girvanella is characteristic of less agitated lagoonal environment, but shallow water".

Spongiostromacean algae are present as oncolites in some of the Goose River facies. They develop about a nucleus of brachiopod valves, stromatoporoid fragments, Amphipora fragments, and other organisms. They were found to occur in sizes up to four centimetres and occur as lemon-shaped structures. Oncolites were found in laminite, dismicrite and sparite rock types. The presence of abundant sparry calcite would suggest a turbulent environment.

Rare, questionable charaphytes (most commonly found in shaly limestone according to Choquette, 1953; hence, probably transported from place to origin to quieter waters) were seen and irregular to circular, white powdery-looking fine calcarenite-size specks were observed in the lagoonal portion of the reef. These white specks are questionably interpreted as algae in origin. Some lime pellets show twisted borings through them which may be algal in nature.

Probably more algae are present in the Goose River reef complex than recorded by the author, but due to sampling technique and their susceptibility to recrystallization, they were not recognized.

Calcispheres

Williamson (1880, p. 521) described calcispheres as "hollow spheres, most of which are furnished with varying forms of peripheral appendages". Within the Goose River reef complex they range in size from fine to coarse calcarenite, are spherical with or without projections (spines or frill), have thin to thick walls, and are generally infilled with calcite. They occur mainly in the lagoonal portion of the reef where their occurrence is recorded as rare to abundant. Since they

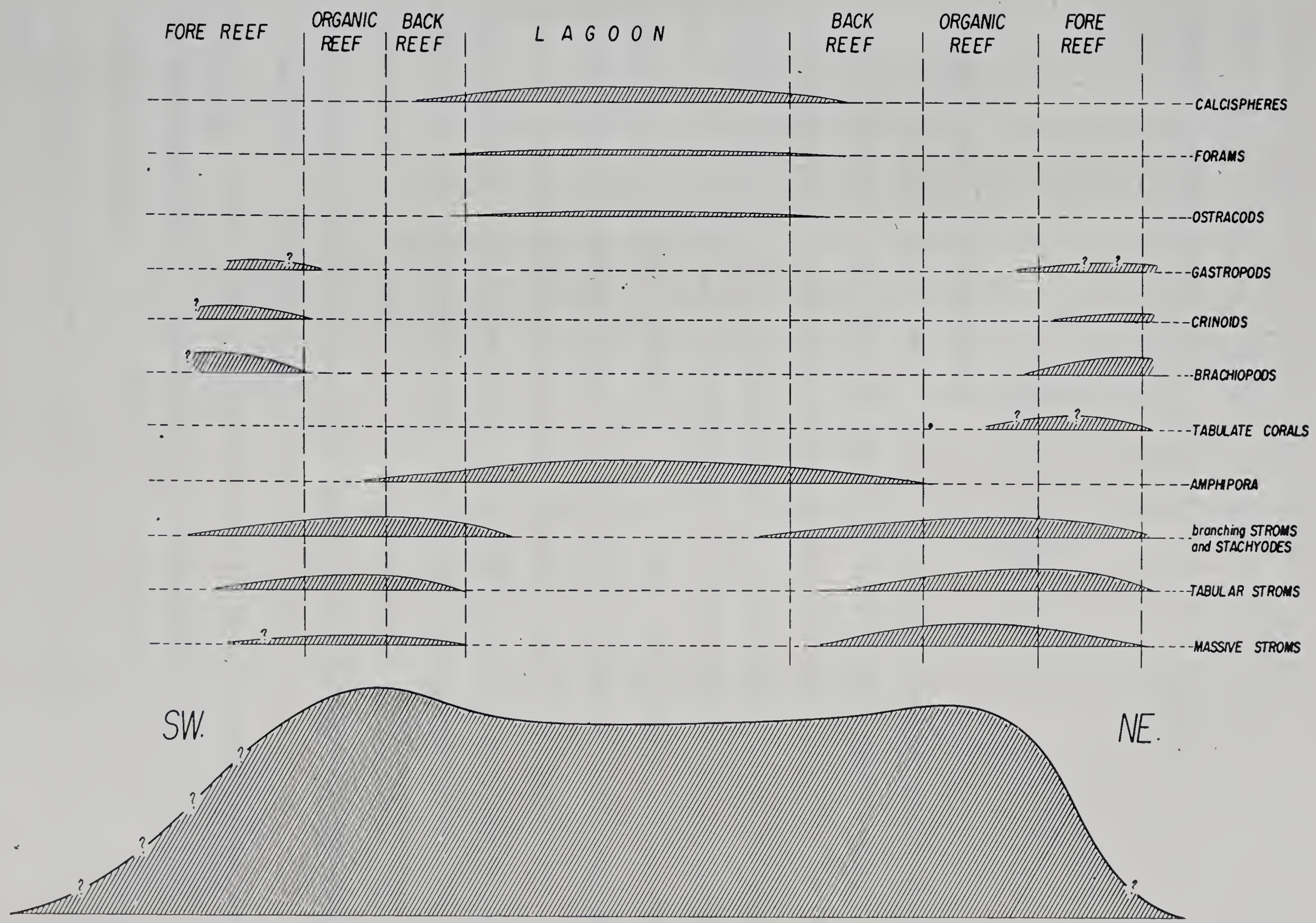


Figure 10.

GENERALIZED DISTRIBUTION OF ORGANISMS IN THE GOOSE RIVER REEF COMPLEX

occur in lime mud rock types they probably preferred quiet water environment or else have been transported from another portion of the reef complex. Their affinity is in doubt. Beales (1961) says, "although a minor constituent volumetrically, calcispheres may have a much greater significance than their sediment contribution".

FACIES ANALYSIS

Gilwood Sand: Quartzose Sandstone

The upper twenty feet of core of the Gilwood sand was examined in the I.O.E. 2-1 well. It was beyond the scope of this work to carry out a detailed examination of this member, but the following analysis is given.

lithology - At the I.O.E. 2-1 well the Gilwood sand consists of a light grey coloured fine to coarse grained sandstone with subrounded to subangular, fairly well sorted grains. The grains are dominantly detrital quartz, but coarse, subrounded to rounded, pitted, blue-grey coloured chert sand grains are also common. Secondary quartz overgrowths (euhedral to subhedral shapes) are common throughout. Rare pink feldspars and black argillaceous rock fragments are present. Anhydrite occurs as fillings of some pore spaces, as do pyrite cubes in part. Fair to good intergranular porosity with traces of dark brown bituminous stains on grain surfaces is found throughout. In part, the examined section shows graded bedding, cross-bedding and thin partings of black shale. A green shale band occurs near the top.

environment - Guthrie (1956) interpreted the Gilwood sand (a member of the Watt Mountain Formation) as a sand deposited by a transgressive sea near the end of Middle Devonian time. Fong (1960) suggests that Gilwood sedimentation is more closely related to the Beaverhill Lake than to that of the underlying pre-Gilwood beds.

"Basal" Beaverhill Lake: Anhydrite and Shale

The lower twenty-five feet of beds in the I.O.E. 2-1 well are designated as "basal" Beaverhill Lake after Fong (1960). A thin, green shaly break is found at the contact with the underlying Gilwood sand and while the upper contact is somewhat gradational with the dark brown micritic limestones of the overlying Dark Brown Submember, a thin, black shale break does occur in this well.

lithology - It consists of alternating beds of dark brown anhydrite and black shale with dark brown micrite limestone in the upper part. The anhydrite has a laminated appearance and is associated in part with dolomite. The shale is partly calcareous and shows fractures completely filled with milk-white anhydrite.

environment - The lithology of this "basal" Beaverhill Lake is interpreted as being formed in a marine environment with restricted circulation.

Swan Hills Member:

The Swan Hills Member attains its greatest thickness, 300 feet, at the I.O.E. 2-1 well. Two units are recognized on the basis of colour and lithology; namely, a lower dark brown unit (stromatoporoid reefal platform) which varies in thickness from eighty to one hundred and twenty feet, and an upper light brown unit (stromatoporoid biohermal reef complex) with variable thickness up to one hundred and eighty feet. The contact between the two units is gradational through interfingering, and as a result, the boundary is difficult to pick either from core or mechanical logs. Examination of the Dark Brown Submember core was carried out only in the I.O.E. 10-15 and 2-1 wells with the result that facies control is lacking laterally within this member. On the other hand, facies in the Light Brown Submember have been better documented, having been investigated in eight wells. Within this Light Brown Submember, laterally non-persistent, thin black and green shaly breaks (referred to as the argillaceous facies) interrupt the carbonate facies. Figure 11 illustrates the facies

through the Goose River Reef Complex.

Petrographic and paleontological constituents (see Table 2) were used to delimit the facies. This delimitation proved very difficult because of the complex nature of the changing variables. As Klovan (1965, p. 44) says, "the mind is not capable of assessing the importance of all these variations simultaneously". It appears then, that the best way to handle so many variables is by using a statistical approach, such as was employed by Klovan. It is unfortunate that the writer did not have sufficient time in this study to try this approach. It must be remembered that the cross-sections (Figure 11) which were constructed to illustrate the distribution of facies through the Goose River reef complex are only an interpretation and hence will be subject to changes as more work is carried out.

The order in which the Swan Hills facies have been described is generally from the bottom of the member upwards (see figure 11), but there is no unique order of facies superposition which holds throughout the reef complex. A generalized environmental grouping of these facies is also shown in figure 11.

FACIES 1: Dark Brown Micritic-crinoid-brachiopod limestone (Plate 4, Figure 1).
lithology - This is a dark brown to black micritic-crinoid-brachiopod, bituminous to argillaceous (?) limestone. Crinoids are scattered throughout, but are common locally in clusters. Whole, dispersed brachiopods are rare to common and some single valves show a sheltered grain effect. Small clusters of whole ostracods and ostracod valves occur very locally. Pelleted to vaguely pelleted grains occur locally with surrounding sparry calcite in this micrite limestone. Irregular vugs filled with dolomite or anhydrite occur in places. Recrystallization of lime mud is evident to some degree. Scattered two-to-three-inch-thick zones of argillaceous and bituminous material are found throughout with enclosed skeletal calcarenite grains and some pyrite. Stylolites occur throughout.

environment - The presence of lime mud and bituminous-argillaceous material suggests a quiet water environment; yet the presence of sparry calcite would indicate some turbulence. The fossils, because of their somewhat abraded and fragmentary nature and their random occurrence, are interpreted as being washed into a quieter water environment. Possibly a fluctuating, quiet to moderately turbulent marine environment persisted at this time.

FACIES 2: Large Strom-Thamnopora limestone (Plate 4, Figures 2-3).

lithology - This is a dark brown to black stromatoporoid-Thamnopora and calcarenite-sized skeletal, bituminous-argillaceous limestone. The fossils - branching stromatoporoids, encrusting and laminar stromatoporoids, *Amphipora*, and Thamnopora type corals (genus *Coenites*) - are fragmentary to somewhat abraded with random orientation throughout. The matrix consists of bituminous-argillaceous matter with subangular calcarenite-sized stromatoporoidal skeletal grains that are ill-sorted. There is a vague indication of recrystallized lime mud in places. Blebs of anhydrite also occur. Stromatoporoids show replacement of some cells by silica. Most fossil voids or cells are infilled with clear sparry calcite and/or dolomite.

environment - The fragmentary to somewhat abraded nature of the fossils and the poorly sorted, subangular skeletal grains are interpreted as being the washed-in or transported constituents from a turbulent shoal area where these organisms dwelled into a quieter marine water environment. The sheltered, quieter water near these shoal areas would be conducive to the deposition of lime mud and bituminous-argillaceous material.

FACIES 3: Dark Brown micritic Amphipora non-skeletal limestone alternating with Amphipora limestone (Plate 4, Figures 4-7)

lithology - This is a dark brown (somewhat bituminous in part) micrite-*Amphipora*

and pellet-lump-intraclast limestone alternating with an Amphipora limestone. Fragmentary Amphipora are scattered throughout, while locally, in six-to-ten-inch-zones they are very abundant and in stylolitic contact. Some Amphipora show recrystallization, as internal structure is becoming indeterminant; only rare Stachyodes were observed. Ostracods and calcispheres are rare to common locally throughout the lime mud. Rare, indeterminant, burrow-like structures also occur. The matrix is mainly lime mud and in part shows a dismicrite appearance where eyes of sparry calcite occur. A vague, laminite appearance is evident occasionally. Calcarenite-sized pellets, lumps, and intraclasts occur throughout while rare, indeterminate skeletal grains occur sparsely. Partial recrystallization of the lime mud is also evident and some anhydrite occurs. Stylolites are common throughout, with brownish bituminous material in the seams.
environment - The presence of sparry calcite and pellet-lump-intraclast grain types suggests some turbulence, while the presence of lime mud suggests that turbulence could not have been too great or have persisted for long. The concentrated, unabraded Amphipora zones probably represent very nearly in-situ accumulation. This rock type was probably deposited in a semi-restricted environment where the slender, fragile Amphipora could still flourish.

FACIES 3a: Laminite and Dismicrite Limestone (Plate 5, Figures 1-2).
lithology - This facies is a subfacies of 3 because it commonly occurs in association with it. It also occurs with facies 9. This is a light to medium brown laminite-dismicrite limestone with rare fossil fragments. The laminite rock types consist of thin layers of lime mud separated by irregular layers of sparry calcite with calcarenite-sized pellets and intraclasts common. Rare skeletal grains were observed.
environment - This rock type is interpreted as being deposited in the tidal-flat environment. See Klovan (1965, p. 50) for further discussion.

<u>FACIES 4: Pisolite-superficial oolite sparite limestone</u> (Plate 5, Figure 3).

<u>lithology</u> - This is a medium to dark brown, well sorted, pisolite-superficial oolite or intraclast, sparry calcite (sparite) limestone with rare fragmentary stromatoporoids scattered randomly throughout. Some intraclasts are in stylolitic contact and rare intergranular porosity is present in places.

<u>environment</u> - A highly turbulent shallow water environment, possibly a tidal channel, is suggested for this rock type because of the well-sorted coated grains and abundance of sparry calcite. Folk (1959) considers pisolites as algal accretions and genetically different from oolites which are physiocochemically precipitated about a nucleus.

<u>FACIES 4a: Non-skeletal and Oncolite sparite limestone</u> (Plate 8, Figures 1-3).

<u>lithology</u> - This is a medium brown, poor to well sorted, calcarenite-sized sparry calcite limestone with <u>Amphipora</u> locally. Fragmentary <u>Amphipora</u> occur sparsely throughout but are common in thin zones with random orientation and in part algal coated. Brachiopod valves occur sparsely and are also algal coated. Oncolites (with <u>Amphipora</u> or brachiopod nuclei) are rounded to subrounded fragments of <u>Parachaetetes</u> are present. The groundmass consists of some pellets, but mainly of intraclasts and coated grains ranging from fine to coarse calcarenite size with sorting varying from poor to very good. The grains are surrounded by sparry calcite. Micrite is rare.

<u>environment</u> - This rock type is interpreted as being formed in a turbulent, shallow water environment, such as a beach or intertidal environment.

<u>FACIES 5: Dark Brown Strom-micritic skeletal limestone</u> (Plate 5, Figures 4-5).

<u>lithology</u> - This is a dark brown stromatoporoid-micritic skeletal limestone. Fragmentary and abraded branching stromatoporoids, encrusting stromatoporoids, massive and

tabular stromatoporoids and rare Amphipora occur throughout. The surrounding material consists of calcarenite-sized skeletal grains with bituminous matter and micrite. Pellets and lumps are found locally with surrounding sparry calcite. Micrite appears to be recrystallized in part to very fine clear calcite. Disseminated pyrite occurs commonly. Stylolites between stromatoporoids are common. Dolomitization of stromatoporoid cells has occurred in part to very fine clear calcite. Disseminated pyrite occurs commonly. Stylolites between stromatoporoids are common. Dolomitization of stromatoporoid cells has occurred in part.

environment - This rock type is difficult to interpret. Abraded and fragmentary macrofossils were probably transported from an agitated water environment and deposited in a deeper quiet water environment where micrite, bituminous matter and pyrite could form. There must have been occasional moderate turbulence because local clusters of pellets and sparry calcite are present.

FACIES 5a: Dark Brown, Euryamphipora-Large strom limestone (Plate 5, Figures 6-7).

lithology - This is a dark brown "Euryamphipora" - stromatoporoid limestone. It is similar to facies 5 except that there is a predominance of the pancake type Amphipora (termed "Euryamphipora" by Klovan, 1965). These pancake Amphipora are found lying in a horizontal position in great abundance. Also present are tabular, encrusting and spheroidal stromatoporoids.

environment - Similar to facies 5, Euryamphipora is probably very nearly in-situ and preferred a somewhat stagnant, quiet, deeper marine water environment.

FACIES 6: Limestone pebble conglomerate (Plate 6, Figure 1).

lithology - This is a medium to dark brown limestone-pebble conglomerate. The micrite pebbles are in stylolitic contact with each other. Amphipora are rare to common, and are surrounded by black to dark brown bituminous-argillaceous material.

environment - This rock type is interpreted as being formed by dessication and tearing up of the sea bottom with transportation into a quiet water environment (possibly a local depression back of the tidal flats). Fragmentary Amphipora were also washed into this same quiet water environment. The stylolitic nature is due to compaction.

FACIES 7: Non-skeletal micrite to dismicrite limestone (Plate 6, Figures 2-3).

lithology - This is a light to medium brown, intraclast-pellet-oncolite micritic limestone, with some laminite structure. Oncolites up to three centimetres in length are common throughout with algae (Girvanella type) coating Amphipora fragments. Ostracods are common locally, calcispheres are rare, and Amphipora are sparsely scattered throughout, lying horizontally. The rock has a laminite appearance in part with pellets and intraclasts common. Some irregular shaped vugs are filled with dolomite. Leached ostracod carapaces contribute some porosity.

environment - Oncolites are believed to form in a turbulent, shallow water environment, so this rock type is interpreted as being formed in a highly agitated shallow water environment.

FACIES 8: Oncolite sparite limestone (Plate 6, Figures 4-5).

lithology - This is a dark brown to medium brown fossil and oncolite-intraclast-coated grain limestone with sparry calcite very common and with some bituminous-argillaceous material in small zones. Oncolites up to three centimetres in size with either brachiopod valves or crinoids as their nucleus occur commonly. Brachiopods and crinoids occur throughout with rare stromatoporoid fragments. The groundmass consists of well-sorted, fine calcarenite-sized intraclasts and algae and/or foraminiferal coated grains, surrounded by sparry calcite. Some

bituminous-argillaceous material occurs in zones. It commonly has a patchy appearance.

environment - This rock type is interpreted as being formed in a turbulent, shallow water environment. The bituminous-argillaceous zones represent periods of quiet water.

FACIES 9: Creamy to buff micritic-Amphipora limestone alternating with Amphipora limestone (Plates 6-7, Figures 1-3 and 6-8).

lithology - This is a creamy to light brown (medium brown in part) micritic skeletal-calcisphere-pellet limestone to an Amphipora limestone. Amphipora is the predominant fossil occurring in this facies and it is found scattered throughout or concentrated in one-to-two-foot zones. Ostracods and calcispheres are scattered throughout, but are common locally in small clusters. In some zones, calcispheres are so abundant that they contribute to the rock name - calcisphere-micritic limestone. Rare branching and massive stromatoporoids were observed. The groundmass consists of fine to medium calcarenite-sized skeletal grains, and where more sparry calcite is common there are pellets, intraclasts and lumps. The matrix is dominantly micrite with some eyes of sparry calcite. The rock has the appearance of a laminite to a dismicrite at some horizons (similar to facies 3a). It differs from facies 3 by colour and by having a greater amount of skeletal grains. The concentrated Amphipora zones usually are a darker brown and are very stylolitic. Forams, charaphytes, algae, and echinoid spines are found throughout in very minor amounts. Macrostylolites occur occasionally.

environment - This is an integrated facies comprised of Amphipora limestone zones, fine calcarenite micrites to dismicrites, and a pellet-calcisphere micrite with Amphipora. Because of the thinness of the various rock units and their complex changing variables these rock types are considered together as one facies. It is predominantly found in the lagoonal part of the reef complex and also interfingering

with the back-reef facies. It is interpreted as being deposited under quiet to moderately agitated conditions. The alternation of mud and spar with pellets and intraclasts suggests deposition at or near wave base. Generally the skeletal grains are fine calcarenite-size and not very abundant. This would suggest that the site of organic growth was some distance away. Because of the abundance of lime mud, the water in the lagoonal area may not have been favourable for organic growth. The concentrated Amphipora zones, which occur throughout, may be a near in-situ accumulation. The environment may have been semi-restricted at times, but not as stagnant as it was for facies 3, which has abundant bituminous material.

FACIES 10: Stachyodes-Amphipora micritic limestone (Plate 7, Figures 4-6).

lithology - This is a light to medium brown Stachyodes-Amphipora micritic limestone. The fossils are mainly Amphipora and Stachyodes in approximately equal proportions with rare gastropods, ostracods and large stromatoporoids. The matrix is mainly micrite with eyes and laminae of sparry calcite with a groundmass of pellets, intraclasts and lumps in various proportions. Rare skeletal grains are also present. Calcispheres are common in parts. Some thin zones show fair to well sorted intraclasts and pellets in sparry calcite with oncolites. It is similar to facies 9 except that Stachyodes are present.

environment - This rock type is interpreted as being formed closer to the site of organic reef growth than facies 9 because of more fragmentary fossils and presence of Stachyodes as well as Amphipora. The presence of pellets, sparry calcite and oncolites suggest a shallow agitated water environment at times with quieter periods indicated by presence of lime mud.

FACIES 11: Strom and skeletal calcarenite limestone (Plate 10, Figures 2-6).

lithology - This is a medium to dark brown stromatoporoid and skeletal limestone

(a biorudite). Tabular, massive and branching stromatoporoids are common throughout. It is cleaner looking than facies 12 and lacks the bituminous-argillaceous and pyritic material. Some fossils appear to be in original position of growth while others are somewhat abraded. The groundmass is calcarenite-sized skeletal grains and dolomite rhombs with fair sorting. Silt-sized, red-brown dolomite grains occur throughout. Irregular-shaped vugs are filled with dolomite mud at times anhydrite. Well developed organic and intergranular porosity is common throughout. Some algal stromatoporoid consortium is present. In some intervals lime mud is found.

environment - This rock type is interpreted as being organic-reef derived material and in part nearly in-situ accumulation. Turbulence was probably moderate to strong because of the sorting of groundmass and the presence of sparry calcite and occasionally lime mud.

FACIES 12: Dark Brown strom-brachiopod-crinoid limestone (Plate 9, Figures 5-7).

lithology - This is a medium to dark brown stromatoporoid and skeletal calcarenite limestone. Matrix consists of medium to coarse calcarenite skeletal matrix with fine to medium calcarenite-sized dolomite rhombs in places. Dark brown bituminous material is common. The stromatoporoids are predominantly tabular and are associated with rare to common, fragmentary massive and branching stromatoporoids. Punctate brachiopods (whole and one valve) and crinoids are common. Some of the brachiopod valves show a sheltered grain effect. The interstitial calcarenite matrix consists of medium to coarse, subrounded to subangular grains of skeletal material (stromatoporoid and brachiopod fragments mainly) and local patches of medium-sized dolomite rhombs. A dark brown bituminous, organic material and silt-sized particles surround the grains. Lime mud and sparry calcite are both rare. Dolomite infilling between fossils occurs locally. Sparry calcite occurs

as filling in fossil cells. Pyrite occurs between skeletal grains, in fossil voids and also on stylolitic seams. Silica replacement in stromatoporoids occurs as ring structures and euhedrals. Poor to fair intrafossil and intergranular porosity occurs locally. The rock is stylolitic throughout with black, bituminous material in the seams; stylolitic contacts between stromatoporoids are also common.

environment - Edie (1961) says that these skeletal calcirudites were formed by local destruction of growing patch reefs during periodic storms. This facies in the I.O.E. 10-15 well suggests a near-reef or fore-reef facies. Turbulence was probably somewhat limited and the depth of water was probably moderate. Because of the presence of bituminous material and pyrite, slightly reducing conditions may have been present. Slumping may also be a common phenomenon in this fore-reef position. It has been observed that when this facies is traced laterally from the I.O.E. 10-15 well through the I.O.E. 4-15 and 2-16 wells that there is a decrease in the amount of dolomite in the matrix and in the degree of dolomitization. This may suggest increasing susceptibility to dolomitization towards the reef rim where magnesium rich intrastratal solutions can more easily migrate. This distribution also appears to be true for the silica replacement phenomenon involving perhaps low pH intrastratal solutions.

FACIES 13: Stachyodes-massive strom constructed limestone (Plate 8, Figures 4-6).

lithology - This is a medium brown stromatoporoid constructed limestone. Fossils are dominantly Stachyodes, with massive, cabbage-like stromatoporoids common locally. Rare cup corals, Amphipora and tabular stromatoporoids are found in parts. Vertically branching Stachyodes with calcarenite grains in between branches indicates organic reef in position of growth. Fossils are somewhat fragmentary, but not abraded. The groundmass consists of fair to well sorted, fine to medium calcarenite-sized dolomite grains. A very little lime mud is present throughout but is common towards the base of the unit. Dolomite filling of vugs is common.

Excellent development of intergranular and organic porosity occurs throughout.
environment - This facies is interpreted as being organic reef in position of growth and in part organically bound limestone.

FACIES 14: Stachyodes-Large strom, skeletal calcarentic limestone (Plate 9, Figures 1-3).
lithology - This is a light to medium brown fragmentary Stachyodes and stromatoporoid-encrusted and skeletal limestone. The fossils are somewhat abraded. Lime mud is rare to absent. The groundmass consists of fair sorted, fine to medium skeletal grains with some sparry calcite. Excellent intergranular to organic development of porosity is common. Dolomite and calcite filling of vugs is also common.
environment - This rock type is interpreted as being deposited in a turbulent environment because of the fragmentary nature of the macrofossils and the well sorted groundmass with lack of lime mud. It was probably deposited very near the organic reef. It may represent a beach deposit.

FACIES 15: Nodular limestone (Plate I, Figure 4).
lithology - This is a medium brownish-grey, patchy to nodular appearing skeletal limestone. Rare, randomly scattered fossil fragments are found throughout. The grains consist of mainly indeterminate fine calcarenite-sized skeletal grains, pellets locally, rock fragments and white algal specks and calcispheres in a finely recrystallized lime mud. Bituminous matter is common, as are stylolites.
environment - This rock type may be interpreted as being formed by dessication of previously deposited carbonate sediment and later reworked by wave action. Another interpretation could be that the partially lithified lime mud was torn up from the sea floor during periodic storm action along tidal channels or unprotected mud flats.

FACIES 16: Skeletal calcarenite limestone (Plate 10, Figure 1).

lithology - This is a medium brownish-grey fine to coarse calcarenite-sized skeletal limestone. Rare, dispersed, fragmentary echinoids, brachiopods, crinoids and stromatoporoids are found throughout. Packing of grains is very close, but some intergranular porosity is evident. Very little lime mud is present, but it appears to be a very fine recrystallized lime mud. Stylolites are common.

environment - This rock is interpreted as being formed in a moderately turbulent environment beyond the organic reef where turbulence is not great enough to transport macrofossils, only sand sized skeletal grains.

FACIES 17: Entangled Amphipora Limestone

lithology - This is a very porous medium brown, entangled *Amphipora* limestone with practically no matrix or groundmass. The *Amphipora* are somewhat abraded. A few indeterminate skeletal calcarenite-sized grains are found occasionally.

environment - The lack of matrix or fine material plus the entangled appearance of the *Amphipora* suggests a beach deposit or an in-situ accumulation.

FACIES 18 and 18a: Dark Brown and Green Shaly Zones

lithology - This is an argillaceous facies which occurs either as green or black shaly bands within the reef complex. These bands which vary in thickness from one-eighth to two inches are discontinuous laterally. It was only between the I.O.E. 10-7 and 10-6 wells that two different stratigraphic green shaly bands were correlative laterally. The green shale is calcareous, non-fissile and in part has subrounded fragments of light to medium brown micritic limestone incorporated in it. The thin black shaly lenses are more closely related compositionally to stylolitic material.

environment - These green shaly zones occur mainly in the lagoonal part of the

reef complex, but they are found sporadically in back-reef areas also. They are interpreted as being deposited in quiet, isolated pools of water on the exposed surface of the reef. The black shaly zones may represent deposition in deep, quiet waters, or as being stylolitic in nature and hence formed by compaction.

"Virginia Hills Member"

The total Beaverhill Lake Formation in the Goose River area varies from a thickness of about 390 to 420 feet, while the thickness of the "Virginia Hills Member" depends upon the interval between the top of the Beaverhill Lake and top of Swan Hills Member (it is thinnest where the Light Brown Submember is thickest - theoretically the "Virginia Hills Member" could be zero thickness if the Light Brown Submember extended to the top of the Beaverhill Lake). In the vicinity of the I.O.E. 2-1 well the "Virginia Hills Member" attains a minimum thickness of about 115 feet while near the I.O.E. 12-23 well it has an average thickness of about 300 feet. At the I.O.E. 10-15 and B.A. 4-3 wells, a three to eight inch "reef rubble zone" is present. A discontinuous twenty foot, lense-like "Coquina Zone" occurs about 155 feet below the top of the Beaverhill Lake in the Goose River area.

lithology - "Reef Rubble Zone" - Reefal pebble conglomerate (Plate 11, Figure 1).

A three to eight inch "reef rubble zone" forms the base of the "Virginia Hills Member". This zone is only present in the rim wells. It consists of sub-rounded to rounded, pebble sized, light to medium brown micritic fossiliferous limestone fragments (intraclasts) surrounded by dark-grey to brownish-black bituminous-argillaceous silty matrix with rare fossil fragments. There is a hetero-genous variety of fossils in the micritic pebbles; namely, stromatoporoid fragments, crinoids, echinoid spines, small gastropods, forams, brachiopod valves,

ostracods, bryozoans, algal fragments, Tentaculites, and other unidentifiable fossils. These fossils are well preserved and scattered randomly throughout. Clear sparry calcite occurs in irregular vugs. Pyrite is very common as replacement of micritic pebbles and of individual fossils. Pyritization of fossils occurs from the outside towards the centre. Micrite pebbles are in stylolitic contact.

environment - This "reef rubble zone" which was observed only in the back-reef and outer slope wells is interpreted as being formed in the following manner: Towards the close of Swan Hills time, lime mud was being deposited in quiet to slightly agitated pools on the reef where also a wide variety of micro-organisms flourished. Following the death of the reef forming organisms the sea destroyed the reef top and deposited the micrite intraclasts and floating micro-organisms in deeper, quieter waters (below wave base) off the rims of the reef complex. Bituminous-argillaceous and pyritic material were later deposited around these fragments. Detailed studies of this zone may produce the clues as to why reef growth terminated.

lithology - "Virginia Hills Member" - Shaly Carbonate (Plate 11, Figures 2-3).

The lithology of the "Virginia Hills Member" consists of a medium dark-grey to dark-brown cryptocrystalline limestone to argillaceous limestone alternating with beds of dark-grey calcareous shale. In general this unit has a patchy appearance (called boudinage by McCrossan, 1959) due to dark brown, rounded micrite-limestone pebbles surrounded by a dark-grey to dark-brown argillaceous to bituminous silt-sized matrix. The dark-grey calcareous shale beds have a platy to conchoidal parting. Brachiopods and crinoids are scattered throughout in the argillaceous parts with local concentration. Rare ostracods, gastropods, and bryozoans were observed. Disseminated pyrite is common throughout and occurs locally as partial replacement of fossils.

environment - A quiet water, marine environment is suggested for the deposition of the "Virginia Hills Member" because of the interbeds of shale and limestone throughout. The nodular to patchy appearance is probably due to compaction (also see Klovan, 1963, p. 141).

lithology - "Coquina Zone" - Echinoderm-bryozoan-brachiopod Coquina (Plate 11, Figures 4-5).

Within the "Virginia Hills Member" at the B.A. 4-3 well, there occurs a twenty foot thick "Coquina Zone". It consists of coarse sand sized, subrounded to subangular skeletal fragments with fair sorting. The skeletal grains are mainly brachiopod valves, crinoids, bryozoans, echinoids, and algal fragments. Some of these skeletal grains show a green colour while others are orange-red. These skeletal grains are surrounded by clear sparry calcite which in places has been partially replaced by milk-white dolomite. Interfragmental porosity occurs where the sparry calcite only partially fills the voids or is lacking (the sonic log indicates streaky, one to two foot intervals of porosity). Macrostylolites are rare, but in thin-section microstylolites between fossil fragments were observed. The I.O.E. 12-23 well is solely producing from this zone, and it is believed that the B.A. 4-3 well is also obtaining production from this zone as well as the Swan Hills Member. In other wells examined a two to five foot, poorly developed crinoidal zone with argillaceous matrix occupies approximately the same stratigraphic position.

environment - This "Coquina Zone" with its well sorted biogenic material and abundant sparry calcite is interpreted as being formed in a highly agitated shallow water environment. It is interesting to note that in the two wells where this "Coquina Zone" was examined the following three facts stand out:

1. it occurs 155 feet below the top of the Beaverhill Lake Formation (see Figure 3).

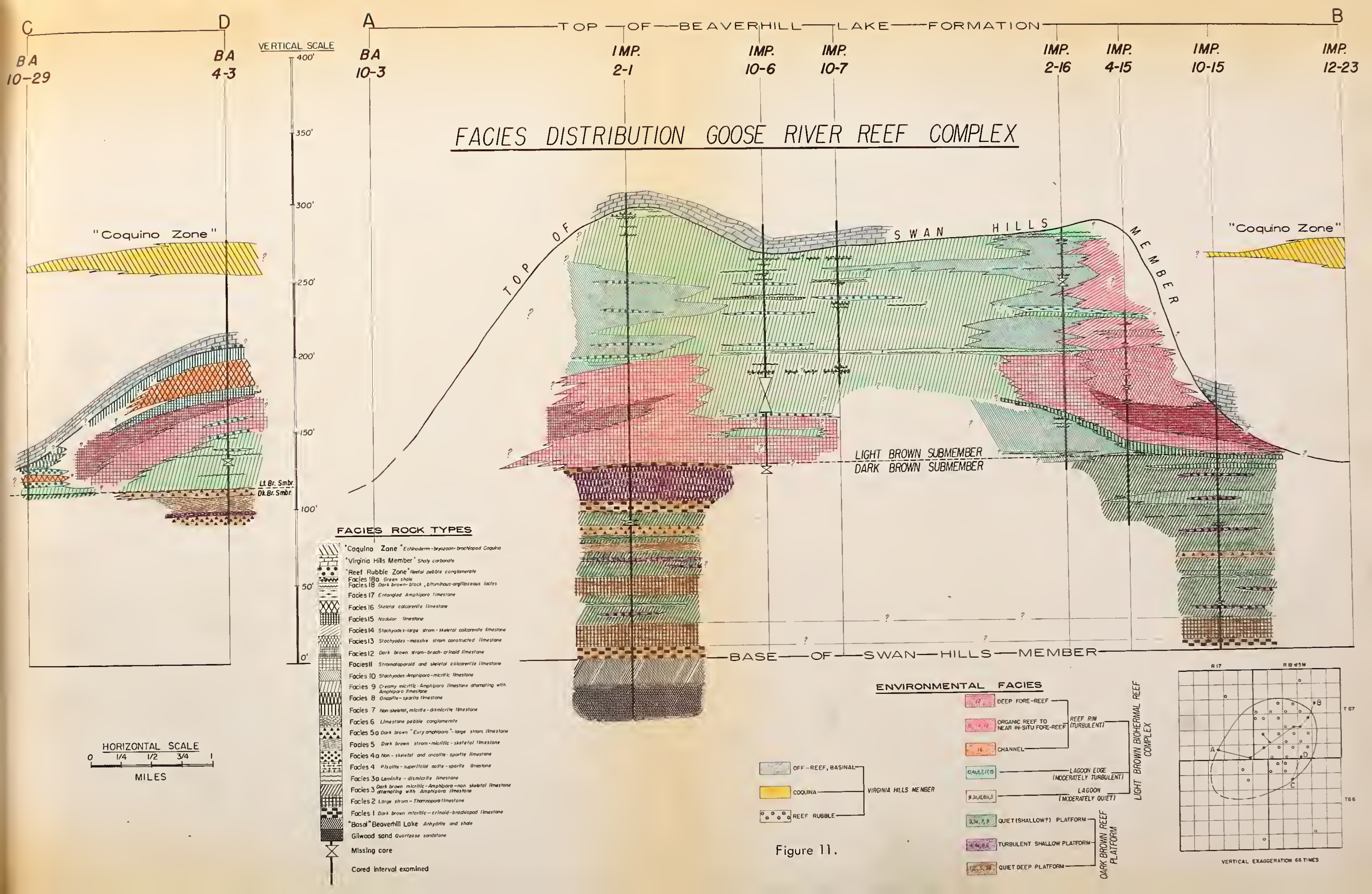
2. in both areas, it is in the vicinity of channels entering the reef complex, and
3. it occurs stratigraphically lower than the highest parts of the reef complex.

Some questions which come to this writer's mind regarding the interpretation of this zone are:

1. What was the source of this biogenic material?
2. What is its stratigraphic relationship to the reef complex?
3. What do the surrounding shaly carbonates of the "Virginia Hills Member" indicate, if anything?

Further detailed study is required to answer these and other questions, but the writer suggests the following interpretation:

1. Reef growth up until this time proceeded normally.
2. A temporary barrier developed to the north-east and east, resulting in a temporary semi-restricted area.
3. There was deposition of thin green shale bands in lagoonal portions of reef complex with some erosion and growth along rims of the reef complex.
4. Sedimentation continued in the basin around the reef complex.
5. Micro-organisms - ostracods, forams, etc. - flourished within, and on the edge of the reef complex.
6. About the time sedimentation in the basin caught up to the reef complex elevation, the barrier to the east and north-east was removed. Renewed current and wave action operating again allowed renewed growth of the reef complex.
7. Micro-organisms were transported, reworked and deposited as local beaches or bars near the reef complex.



FACIES DISTRIBUTION GOOSE RIVER REEF COMPLEX
C
D
A
B
TOP OF BEAVERHILL LAKE FORMATION
BA 10-29
BA 4-3
BA 10-3
IMP. 2-1
IMP. 10-6
IMP. 10-7
IMP. 2-16
IMP. 4-15
IMP. 10-15
IMP. 12-23
VERTICAL SCALE
400'
350'
300'
250'
200'
150'
100'
50'
0'
"Coquino Zone"
"Coquino Zone"
TOP OF SWAN HILLS MEMBER
Lt. Br. Smbr.
Dk. Br. Smbr.
LIGHT BROWN SUBMEMBER
DARK BROWN SUBMEMBER
BASE OF SWAN HILLS MEMBER
HORIZONTAL SCALE
0 1/4 1/2 3/4 1
MILES
FACIES ROCK TYPES
"Coquino Zone" Echinoderm-bryozoan-brachiopod Coquina
"Virginia Hills Member" Shaly carbonate
"Reef Rubble Zone" Reefal pebble conglomerate
Facies 18a Green shale
Facies 18 Dark brown-black, bituminous-argillaceous facies
Facies 17 Entangled Amphipora limestone
Facies 16 Skeletal calcarenite limestone
Facies 15 Nodular limestone
Facies 14 Stachyodes-large strom-skeletal calcarenite limestone
Facies 13 Stachyodes-massive strom constructed limestone
Facies 12 Dark brown strom-brach-crinoid limestone
Facies 11 Stromatoporoid and skeletal calcarenite limestone
Facies 10 Stachyodes-Amphipora-micritic limestone
Facies 9 Creamy micritic-Amphipora limestone alternating with Amphipora limestone
Facies 8 Oncolite-sparite limestone
Facies 7 Non-skeletal, micrite-dismicrite limestone
Facies 6 Limestone pebble conglomerate
Facies 5a Dark brown "Euryamphipora"-large strom limestone
Facies 5 Dark brown strom-micritic-skeletal limestone
Facies 4a Non-skeletal and oncolite-sparite limestone
Facies 4 Pisolite-superficial oolite-sparite limestone
Facies 3a Laminite-dismicrite limestone
Facies 3 Dark brown micritic-Amphipora-non skeletal limestone alternating with Amphipora limestone
Facies 2 Large strom-Thamnopora limestone
Facies 1 Dark brown micritic-crinoid-brachiopod limestone
"Basal" Beaverhill Lake Anhydrite and shale
Gilwood sand Quartzose sandstone
Missing core
Cored interval examined
ENVIRONMENTAL FACIES
OFF-REEF, BASINAL
COQUINA
REEF RUBBLE
VIRGINIA HILLS MEMBER
12 DEEP FORE-REEF
11, 14, 13 ORGANIC REEF TO NEAR IN-SITU FORE-REEF
16 CHANNEL
REEF RIM (TURBULENT)
LAGOON EDGE (MODERATELY TURBULENT)
9, 3a, 18, 18a, 3 LAGOON (MODERATELY QUIET)
LIGHT BROWN BIOHERMAL REEF COMPLEX
3, 3a, 7, 9 QUIET (SHALLOW?) PLATFORM
TURBULENT SHALLOW PLATFORM
QUIET DEEP PLATFORM
DARK BROWN REEF PLATFORM
R 17
R 18 W5M
T 67
T 66
VERTICAL EXAGGERATION 66 TIMES

Figure 11.

8. Finally there was a return to normal conditions of reef growth on the reef complex.

INTERPRETATION OF REEF DEVELOPMENT

From the numerous studies carried out on modern day reefs, it has been found that the origin and development of reefs is controlled by a delicate interplay of such factors as (1) climate and latitude, (2) current and tidal influence, (3) temperature and depth of water, (4) sea bottom relief, (5) rate of subsidence, (6) amount of terrigenous material supplied to the area, (7) amount and type of nutrients, (8) chemistry of the water, (9) competition amongst different organisms, (10) activity of major organism reef builders, and others. Applying a fundamental geologic principle; namely, that "the present is the key to the past" the above factors must have influenced to varying degrees the reef growths in the geologic past. There is one major difference in geographic setting between modern day and ancient reefs, and that is that most modern day reefs are surrounded by very deep water (for example, the Bahamas) while most ancient reefs developed in epicontinental seas. The closest present day similarity in setting to our Devonian reefs is perhaps found in the Campeche Bank in the Gulf of Mexico.

During very early Upper Devonian time in the Goose River area, the platform surrounding the Peace River High had a favourable geographic setting for Swan Hills reef growth. Here in a marine environment of an epicontinental sea, abundant stromatoporoids flourished as current and wave action supplied the necessary nutrients for reef growth. The climate also must have been suitable. Initially a biostromal or platform reef (Dark Brown Submember) developed, and on small, isolated highs (see Figure 7) biohermal reef (Light Brown Submember) began to grow. The facies distribution cross-sections (Figure 11) indicate that this

stromatoporoid biohermal reef complex was atoll-like in development. A comparison with Edie's (1961) interpretation of reefal development in the Swan Hills Field shows that the Goose River reef complex is similar to his stage "B". A continual rise in sea level allowed for upward and lateral reef growth with the result that an atoll-like reef developed. Reef growth may have terminated with an increase in subsidence, or shallowing or withdrawal of the sea.

CONCLUSIONS

From the foregoing petrographic and paleontologic analyses of the Swan Hills Member and some associated facies, the following has been concluded:

1. The distribution of the various facies across the reef complex suggests an atoll-like reef development comparable to stage "B" of Edie's (1961) interpretation of reef growth in the Swan Hills field; however, identification of organic reef is difficult, and further detailed study may alter the writer's interpretation.

2. Fore-reef, organic reef, back-reef and lagoonal facies have been differentiated within the reef complex. The areal boundaries are somewhat flexible since interfingering of facies occurs.

3. Laminite and dismicrite rock types occur most commonly in association with micrite limestones, and this is mainly in the lagoonal part of the reef complex. They are also found within the Dark Brown Submember.

4. Biocalcarenites and biocalcirudites occur most commonly in rim positions of the reef complex, for it is here that energy conditions were high enough to break down the organic reef framework.

5. The best development of porosity is in rim wells where it occurs as intergranular and organic pore spaces; the poorest development of porosity is in

the lagoonal part of the reef complex where there is a high percentage of micrite. Leaching of ostracods is a common phenomenon.

6. A lateral zonation of organisms was found to be present across the reef complex; namely,

(a) large stromatoporoids, brachiopods and crinoids are present in the fore-reef position,

(b) organic reef and/or near in-situ accumulation consists of Stachyodes and large stromatoporoids,

(c) large stromatoporoids and Stachyodes are present in the back-reef position,

(d) the lagoonal part of the reef complex consists mainly of Amphipora with minor occurrences of forams, ostracods and calcispheres.

It appears that Amphipora flourished in a not too highly agitated environment as did the large and branching stromatoporoids. The concentrated Amphipora zones suggest near in-situ accumulation and these are mainly in the lagoonal part of the reef where presumably energy conditions were low relative to the reef front.

7. Algae appear to have played a very minor role in reefal development in this complex.

8. From a study of isopachous maps, structural maps, and cross-sections, the following reef geometry was deduced:

(a) the crest of the reef is located in the southwestern part of the reef complex where it attains a thickness of at least 300 feet,

(b) an isopachous map of the Dark Brown Submember indicates three possible loci for initiation of Light Brown Submember biohermal reef growth. These areas also correspond to highs on the reef complex,

(c) profiles across the reef complex show a reef crest, gentle back slope, outer slope and lagoonal area,

(d) three prominent channels connect the reef complex with the basin.

9. An off-reef, laterally discontinuous echinoderm-bryozoan-brachiopod "Coquina Zone" appears to be associated with the environment in the vicinity of intra-reef - basinward channels. It is interpreted as being formed in a turbulent, shallow water environment such as a beach.

10. The most noticeable diagenetic changes are an increase in dolomitization and silica replacement towards fore-reef positions and towards the base of the reef. This susceptibility to dolomitization and silica replacement may be due to the ease of migration of magnesium and silica rich solutions in the fore-reef position.

11. If stylolites are a response to compaction the abundant stylolites present in the reef complex suggest removal of a considerable amount of material from the reef. The writer calculated a loss of 9.2 percent of material in 448.25 inches of core, measuring only the larger stylolites. The importance of stylolites should be further investigated.

12. Termination of reef growth may have been due to rapid subsidence as indicated by the presence of shaly calcium carbonate in the "Virginia Hills Member". Further study should be carried out on the so-called "reef rubble zone" for it may provide clues to the cause of the cessation of reef growth.

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EXPLANATION OF PLATE 1

Stylolites

Figure 1. Hand specimen of stylolitic contacts between branching and encrusting stromatoporoids. Sutures show little relief and the thin seams are composed of brownish-black material. (X1).

Figure 2. Peel, similar to Figure 1, but coarser groundmass. Note branching stylolites. (X1)

Figure 3. Hand specimen of prominent stylolites in a relatively unfossiliferous, skeletal calcarenite-micritic limestone. Height of stylolite about 1 inch. Note how thickness of material on seams varies; seams are thickest in culminations and depressions. (X1)

Figure 4. Hand specimen of stylolites between *Amphipora* in an *Amphipora* facies. (X1)

Figure 5. Hand specimen of a very stylolitic *Amphipora* limestone. Note how stylolites branch. The thicker black seams may actually represent a hiatus. (X1)

Figure 6. Peel showing stylolitic contact between two different rock types. This is a common occurrence in the Goose River reef complex. (X1)

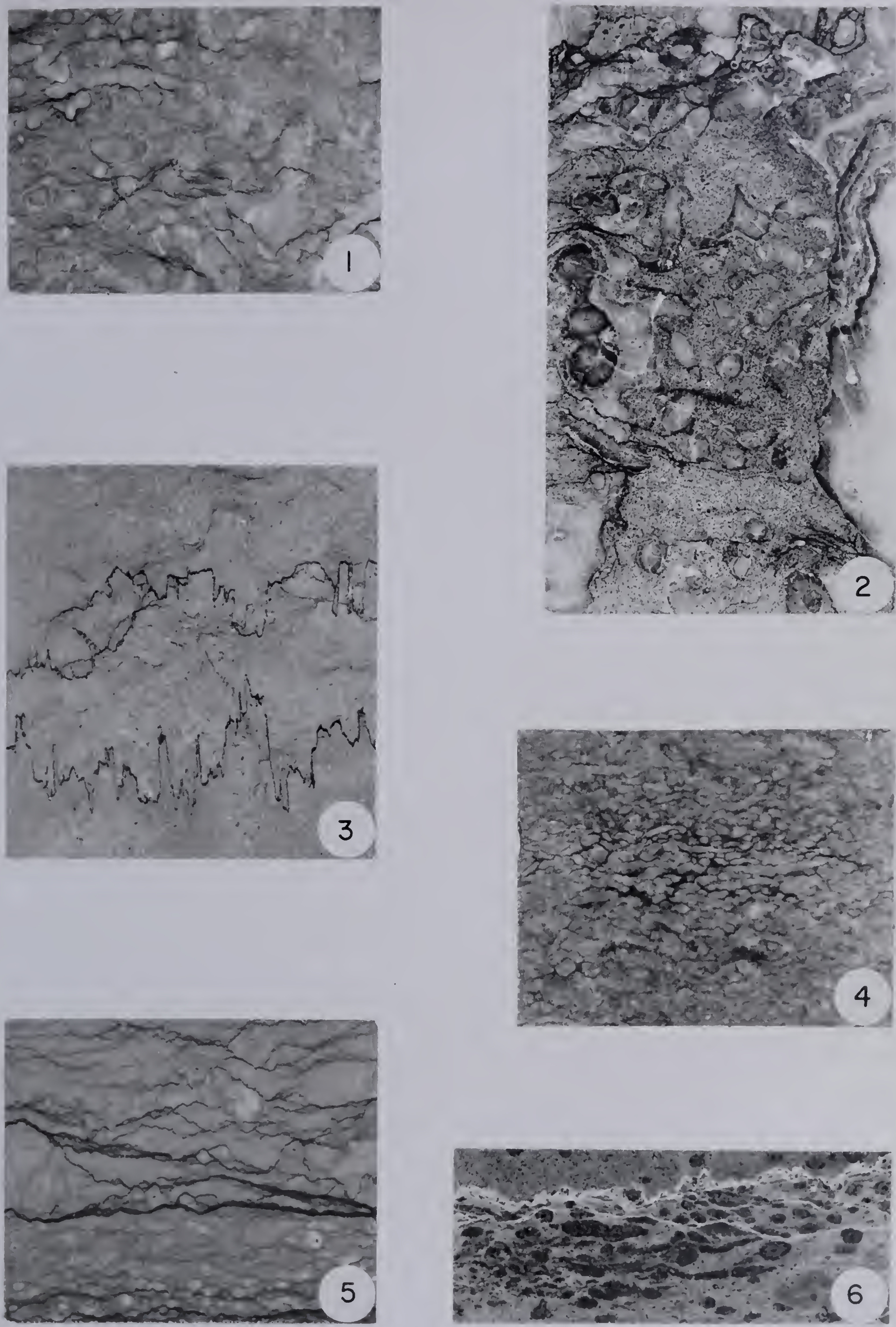

PLATE I.

EXPLANATION OF PLATE 2

Petrography and Paleontology

(all figures are thin sections taken in transmitted light)

Figure 1.	Recrystallized calcite. Note large crystal size in right half of photo. (X50)
Figure 2.	Calcisphere showing frill structure; interior filled with sparry calcite. Recrystallization of lime mud in lower part of photo. (X50)
Figure 3.	Pellets and intraclasts surrounded by sparry calcite cement. Some partly recrystallized, others well preserved. (X50)
Figure 4.	Intraclasts surrounded by sparry calcite cement. (X120)
Figure 5.	Well preserved ostracods in partly recrystallized lime mud (X50)
Figure 6.	Magnification of Figure 5. Note two generations of sparry calcite. (X320)
Figure 7.	Dolomite rhombs in lime mud (X126)
Figure 8.	Silica euhedral replacement of large stromatoporoid cell. (X126)

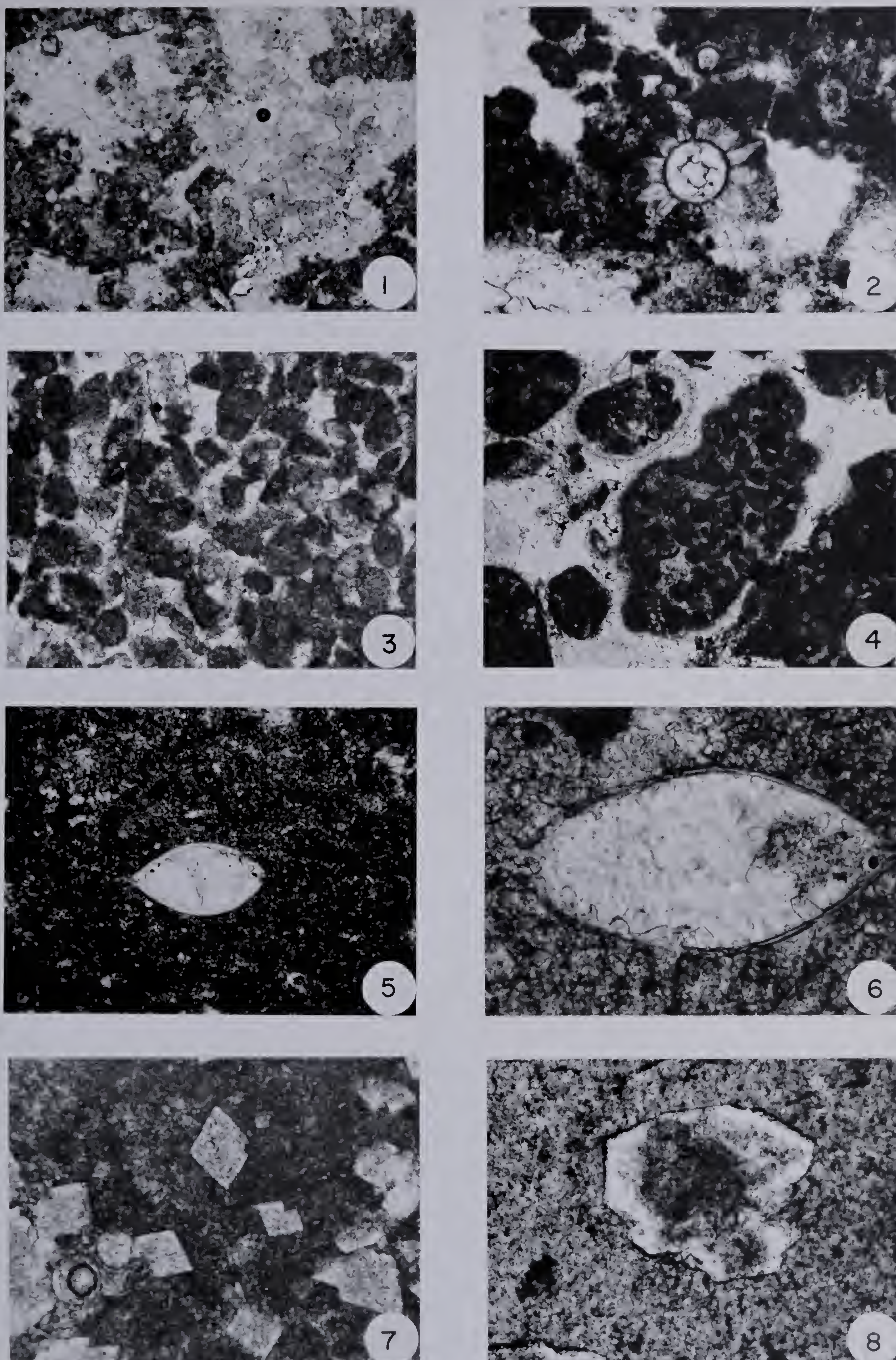

PLATE 2.

EXPLANATION OF PLATE 3

Petrography and Paleontology

(note, peels are negative photographs)

Figure 1. Thin section of disrupted brachiopod valve in bituminous, micritic limestone. (X50)

Figure 2. Thin section of calcite infilled fissure in partly recrystallized lime mud (X320)

Figure 3. Thin section of sparry calcite infilled central canal and marginal vessicles in Amphipora (X50)

Figure 4. Thin section of the algae Parachaetetes (reflected light) (x50)

Figure 5. Hand specimen of tabular stromatoporoid. Note anhydrite infilling on right of photo. (X1)

Figure 6. Peel of cup coral, Tabulophyllum. Note branchiopod valves in lower part of photo. (X2)

Figure 7. Peel of stromatoporoid encrusted coral in skeletal calcarenite matrix. (X2)

Figure 8. Peel of massive stromatoporoid with dolomite infilling of cells. Dispersed Amphipora in upper part of photo (X1)

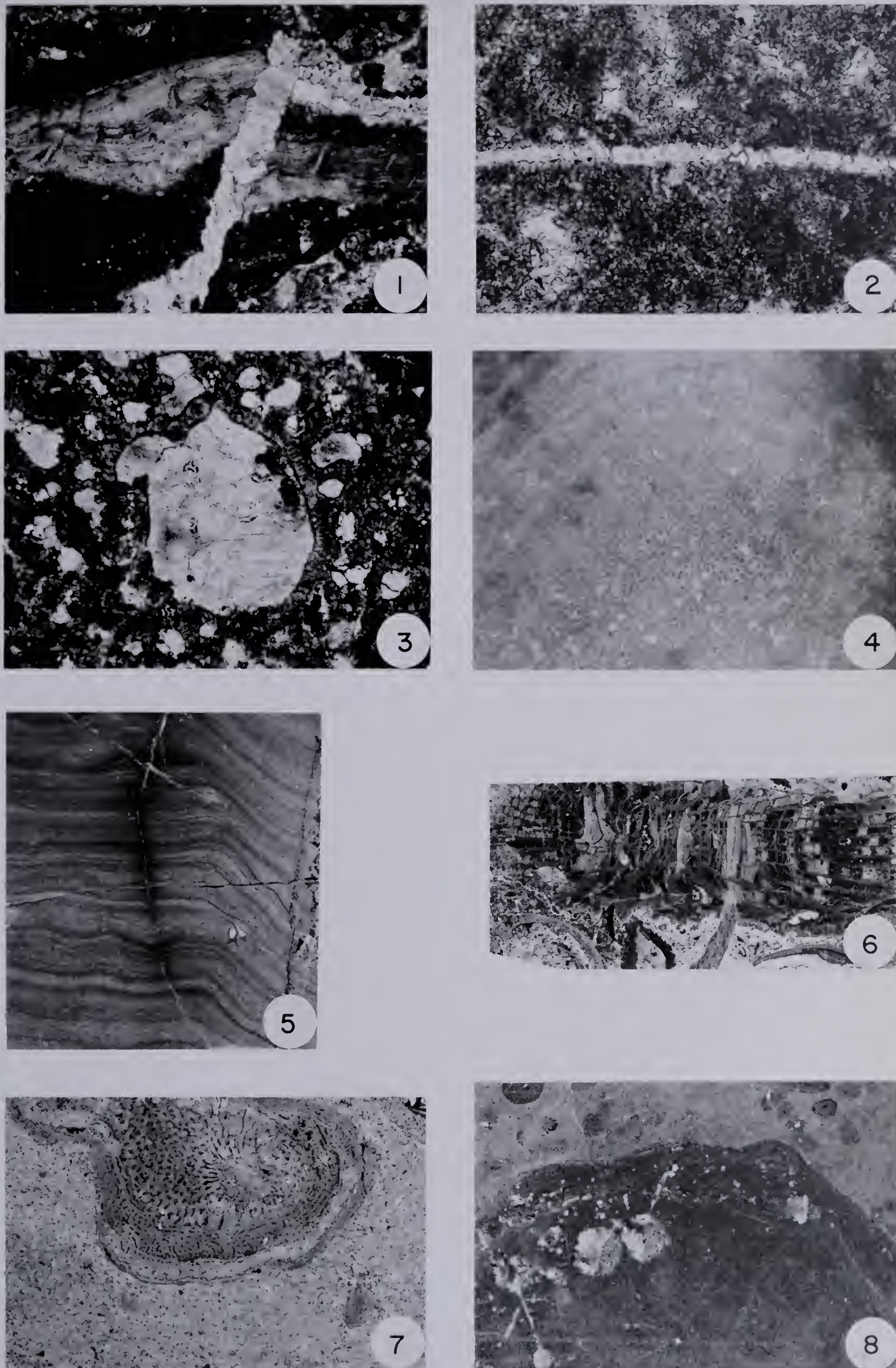

PLATE 3.

EXPLANATION OF PLATE 4

Goose River Rock Types

Figure 1. Facies 1 - Hand specimen of dispersed crinoid fragments in a dark brown, micritic-bituminous-stylolitic limestone. (X1)

Figure 2. Facies 2 - Thin section of coarse, sand-sized skeletal grains in a bituminous, micritic matrix (X50)

Figure 3. Facies 2 - Peel showing fragmental stromatoporoids and *Thamnopora* in upper centre of photo. Note coarse skeletal groundmass. (X2)

Figure 4. Facies 3 - Thin section showing stylolites, partly recrystallized lime mud and vaguely defined pellets (X126)

Figure 5. Facies 3 - Hand specimen of poorly laminate rock type at top of photo to dismicrite with dispersed *Amphipora* fragments. (X1)

Figure 6. Facies 3 - Thin section showing pellets and intraclasts surrounded by sparry calcite cement. Note recrystallization of some grains (X126)

Figure 7. Facies 3 - Peel showing a micritic limestone with dispersed *Amphipora* overlying in stylolitic contact an *Amphipora* limestone (X1)

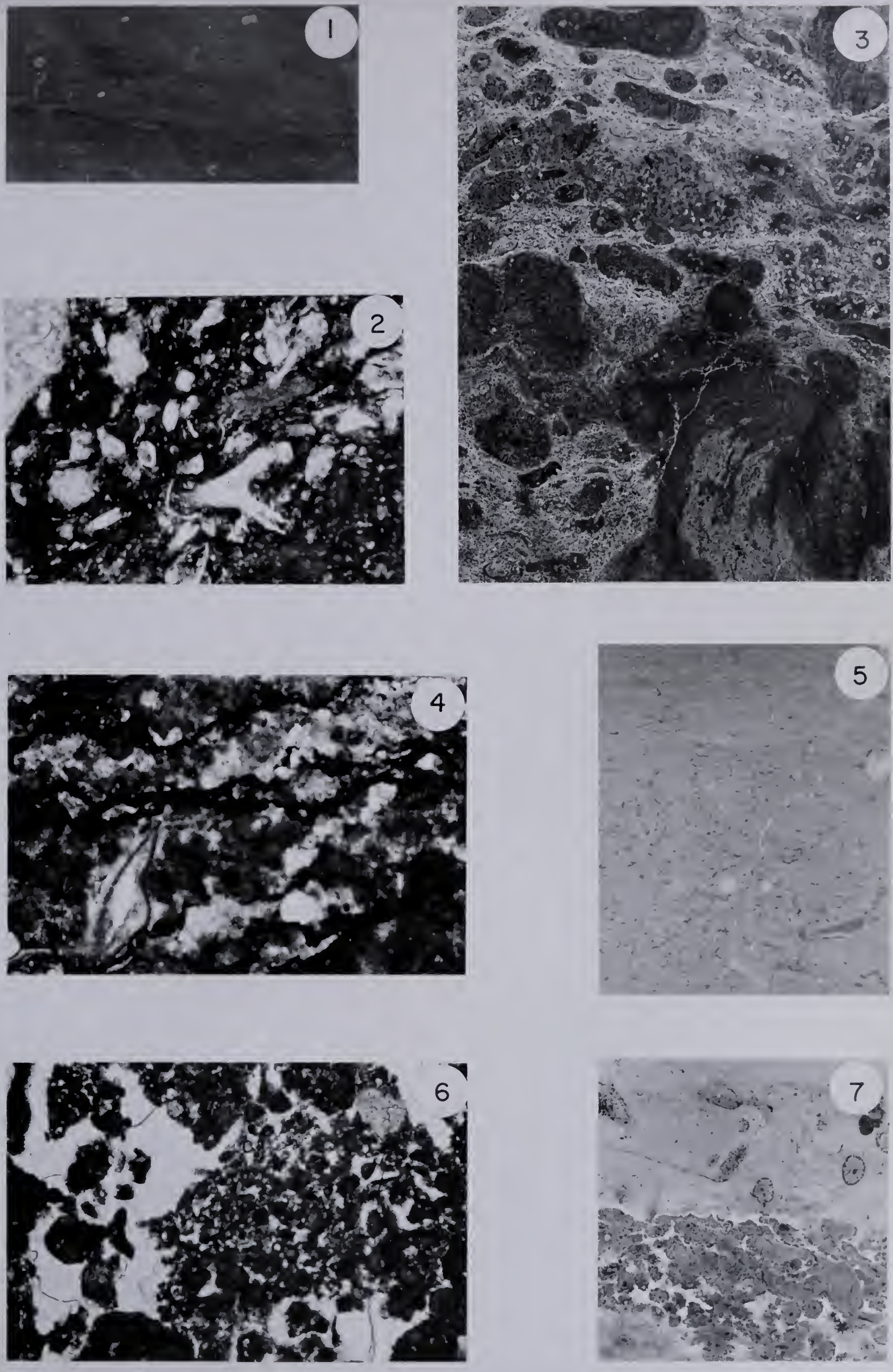

PLATE 4.

EXPLANATION OF PLATE 5

Goose River Rock Types

Figure 1. Facies 3a - Peel of a dismicrite limestone. (X1)

Figure 2. Facies 3a - Peel of a laminite. A green shaly break occurs at top of photo. (X1)

Figure 3. Facies 4 - Thin section (reflected light) showing pisolites and superficial oolites. (X50)

Figure 4. Facies 5 - Hand specimen showing Stachyodes, encrusting stromatoporoids and a spheroidal stromatoporoid in a dark brown micritic limestone with some skeletal grains. (X1)

Figure 5. Facies 5 - Hand specimen of fragmental, tabular stromatoporoids surrounded by skeletal-bituminous-micritic matrix. (X1)

Figure 6. Facies 5a - Hand specimen of pancake type stromatoporoids named "Euryamphipora" by Klovan (1965). (X1)

Figure 7. Facies 5a - Hand specimen showing fragmental "Euryamphipora" and spheroidal stromatoporoids surrounded by a dark brown bituminous-micritic matrix (X1)

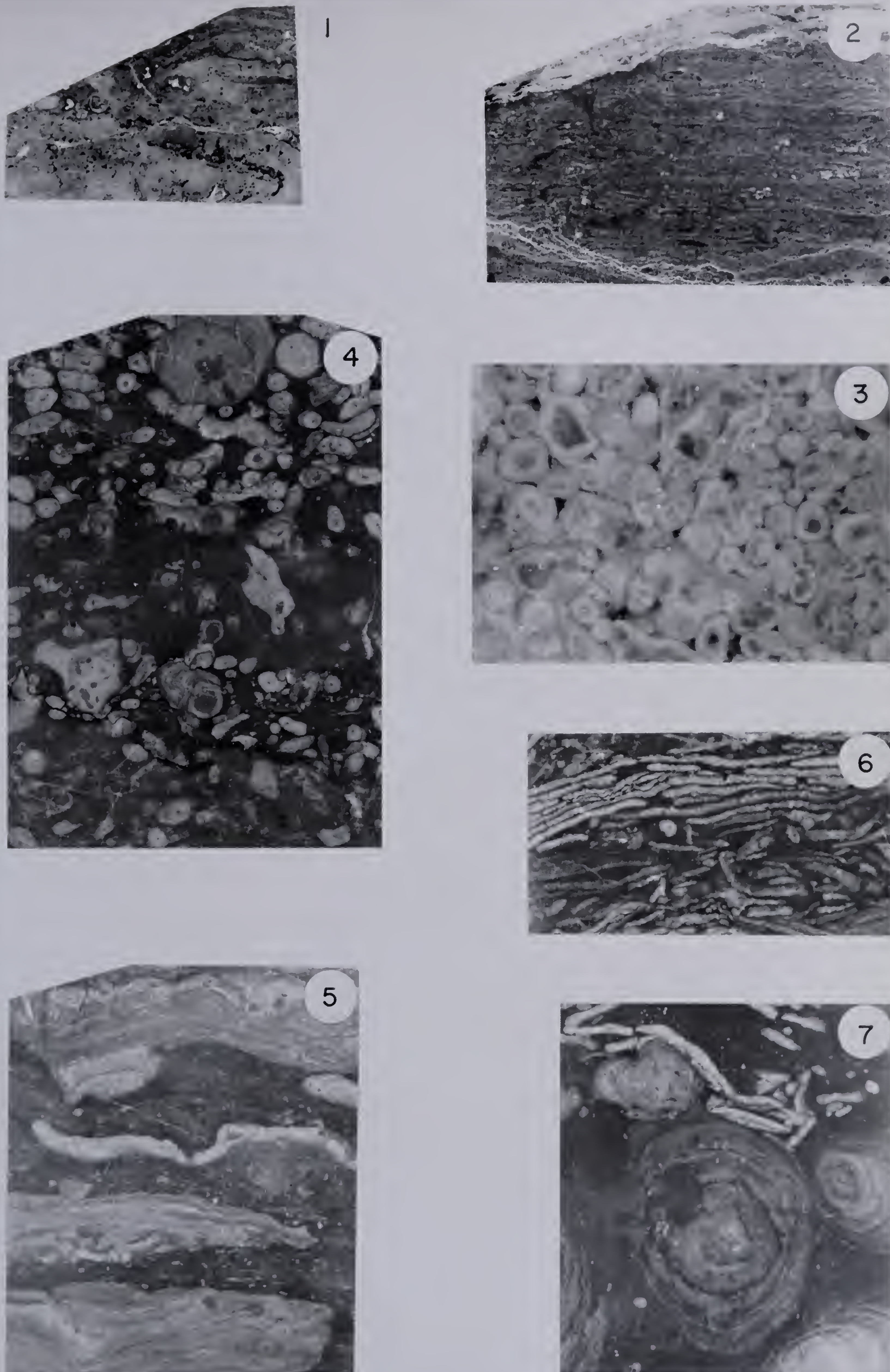

PLATE 5.

EXPLANATION OF PLATE 6

Goose River Rock Types

Figure 1. Facies 6 - Hand specimen of a stylolitic, micritic limestone pebble conglomerate. (X1)

Figure 2. Facies 7 - Peel showing an oncolite and some dispersed *Amphipora* fragments in a dismicrite limestone. (X1)

Figure 3. Facies 7 - Thin section of an intraclast - (some pellets?) sparite limestone. (X50)

Figure 4 & 5. Facies 8 - Peels showing oncolites and crinoidal debris. Sparry calcite is the cement. (X1)

Figure 6. Facies 9 - Peel of dispersed *Amphipora* in a micritic-sand sized skeletal limestone. Note massive stromatoporoid in lower right of photo. (X1)

Figure 7. Facies 9 - Peel of spheroidal stromatoporoid with some vacuoles infilled with dolomite. (X1)

Figure 8. Facies 9 - Peel of a dismicrite with some irregular vugs filled with dolomite. (X1)

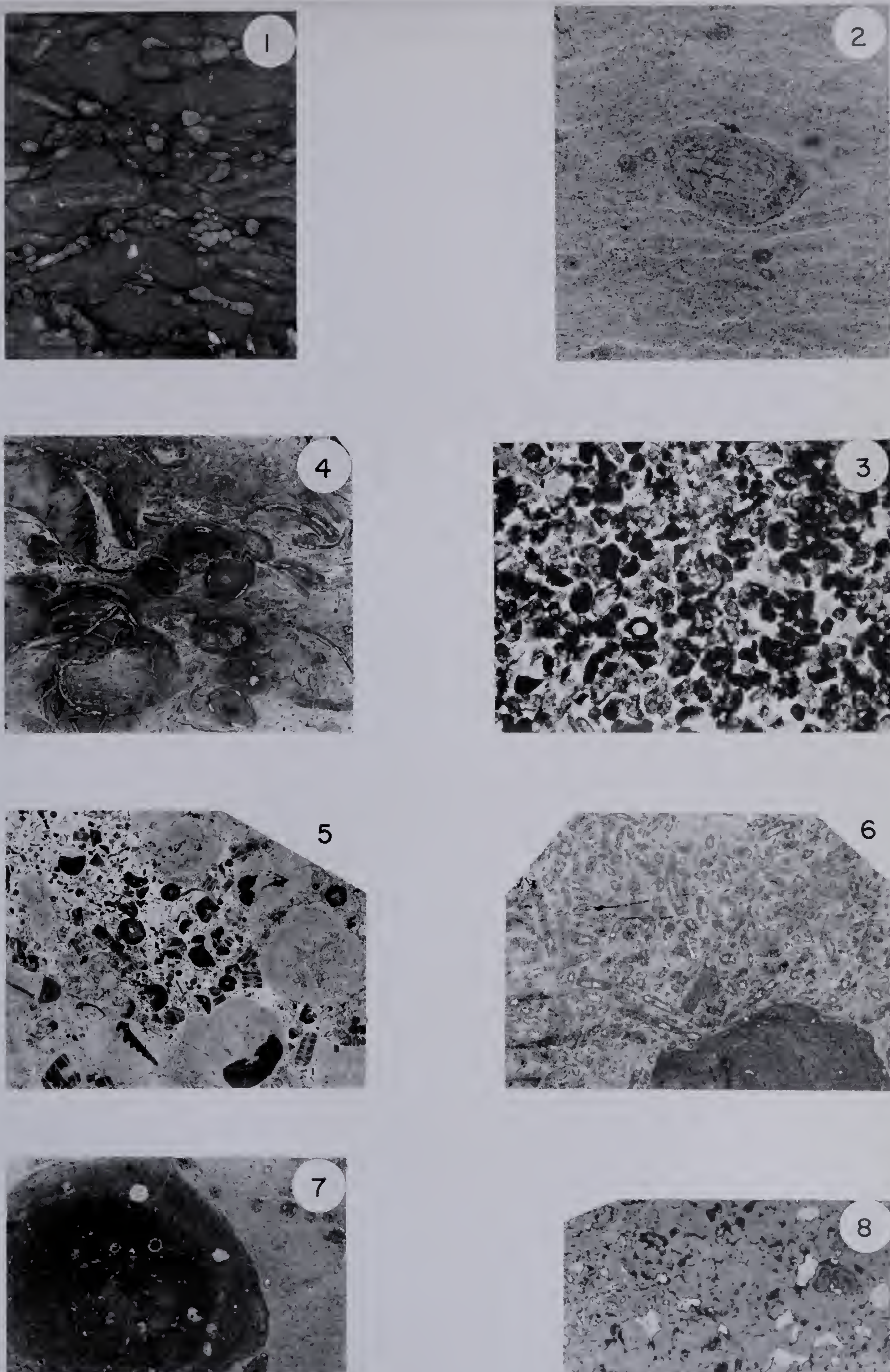

PLATE 6.

EXPLANATION OF PLATE 7

Goose River Rock Types

Figure 1. Facies 9 - Hand specimen of Amphipora limestone. (X1)

Figure 2. Facies 9 - Hand specimen showing fragmental and a coated Amphipora in a micritic-skeletal matrix. Note stylolitic nature at top of photo. (X1)

Figure 3. Facies 9 - Thin section showing calcispheres in a micrite to partly recrystallized micrite limestone. (X50)

Figure 4. Facies 10 - Peel of Amphipora and rare Stachyodes in a micritic-skeletal matrix. (X1)

Figure 5. Facies 10 - Thin section showing intraclasts and calcispheres surrounded by sparry calcite and partly recrystallized lime mud. (X50)

Figure 6. Facies 10 - Peel of fragmented branching stromatoporoids with rare Amphipora in micritic-skeletal matrix. (X1)

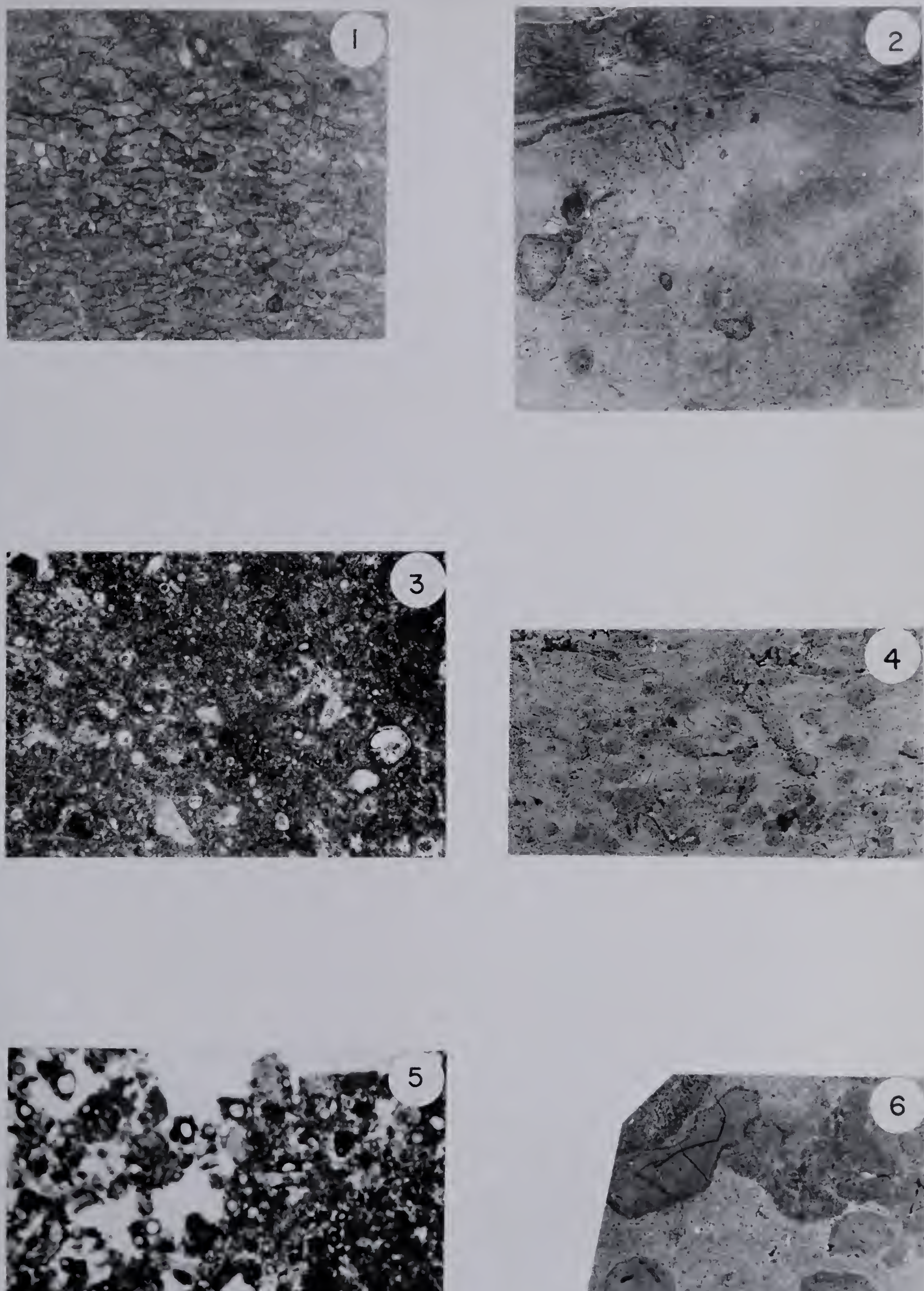

PLATE 7.

EXPLANATION OF PLATE 8

Goose River Rock Types

Figures 1-2	Facies 4a - Thin sections of well sorted and poorly sorted intraclast-pellet sparite limestone. (X50)
Figure 3.	Facies 16 - Peel of coated, fragmental *Amphipora* limestone. (X1)
Figures 4-6.	Facies 13 - Peels of stromatoporoidal constructed limestone - organic (?) reef. Note high organic porosity. (Figure 4 is X1 while figures 5-6 are X2).

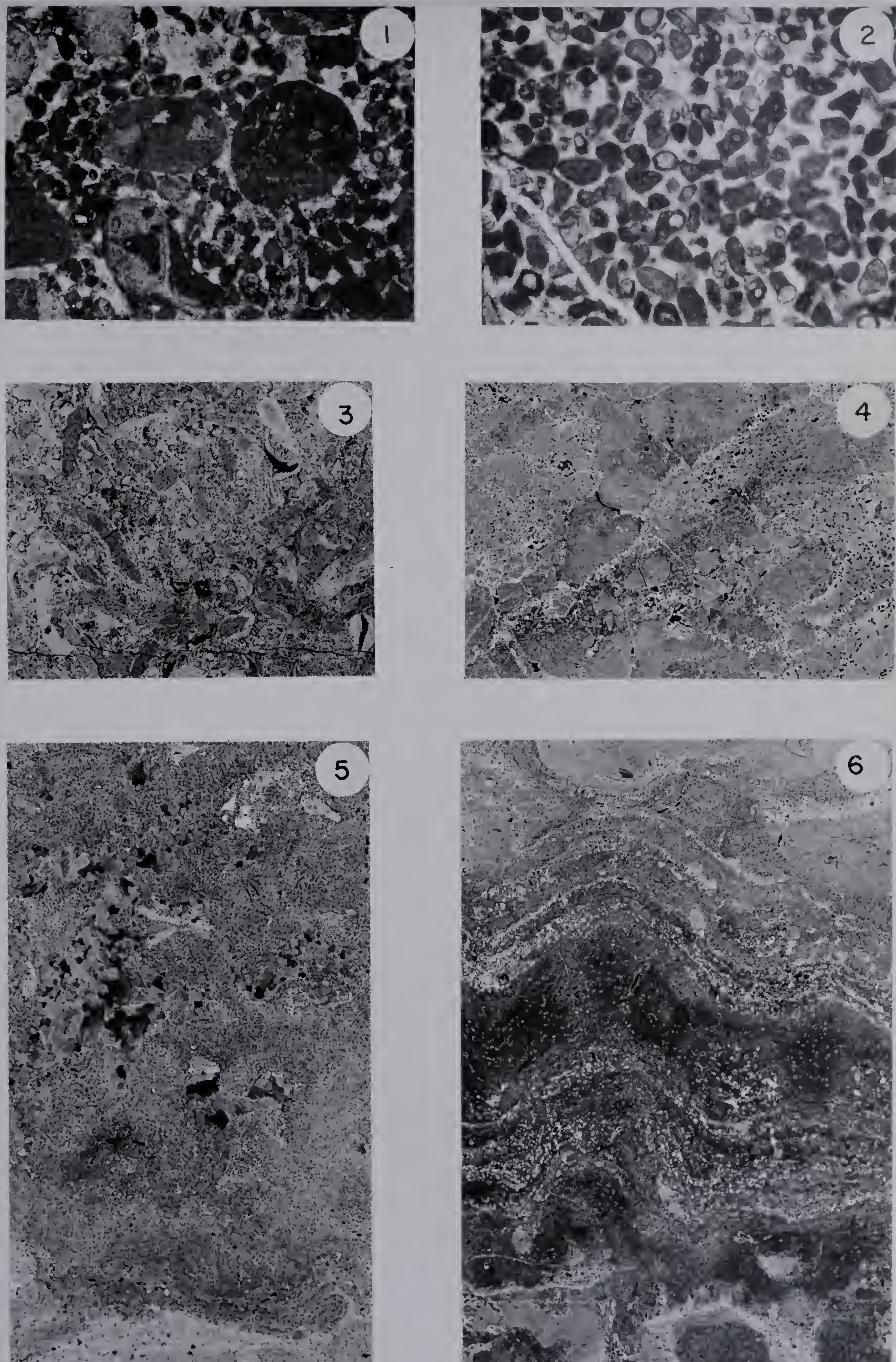

PLATE 8.

EXPLANATION OF PLATE 9

Goose River Rock Types

Figure 1. Facies 14 - Peel of fragmental and coated Amphipora. Note high porosity and some secondary dolomite filling between fossils. (X1)

Figure 2. Facies 14 - Peel of Stachyodes with well developed organic porosity. Groundmass consists of skeletal grains (X2)

Figure 3. Facies 14 - Thin section of skeletal calcarenite with well developed intergranular porosity. Note good sorting. (X50)

Figure 4. Facies 15 - Hand specimen of disrupted micritic-skeletal limestone. Note dispersed fossil fragments and numerous stylolites. (X1)

Figure 5. Facies 12 - Peel of fragmented tabular stromatoporoids, brachiopod valves and other fossil fragments surrounded by skeletal matrix. (X1)

Figure 6. Facies 12 - Thin section showing dolomite rhombs and skeletal grains in a bituminous, somewhat micritic matrix (X50).

Figure 7. Facies 12 - Peel of fragmented massive stromatoporoid with surrounding skeletal calcarenite matrix. Note recrystallization on left edge of photo. (X2)

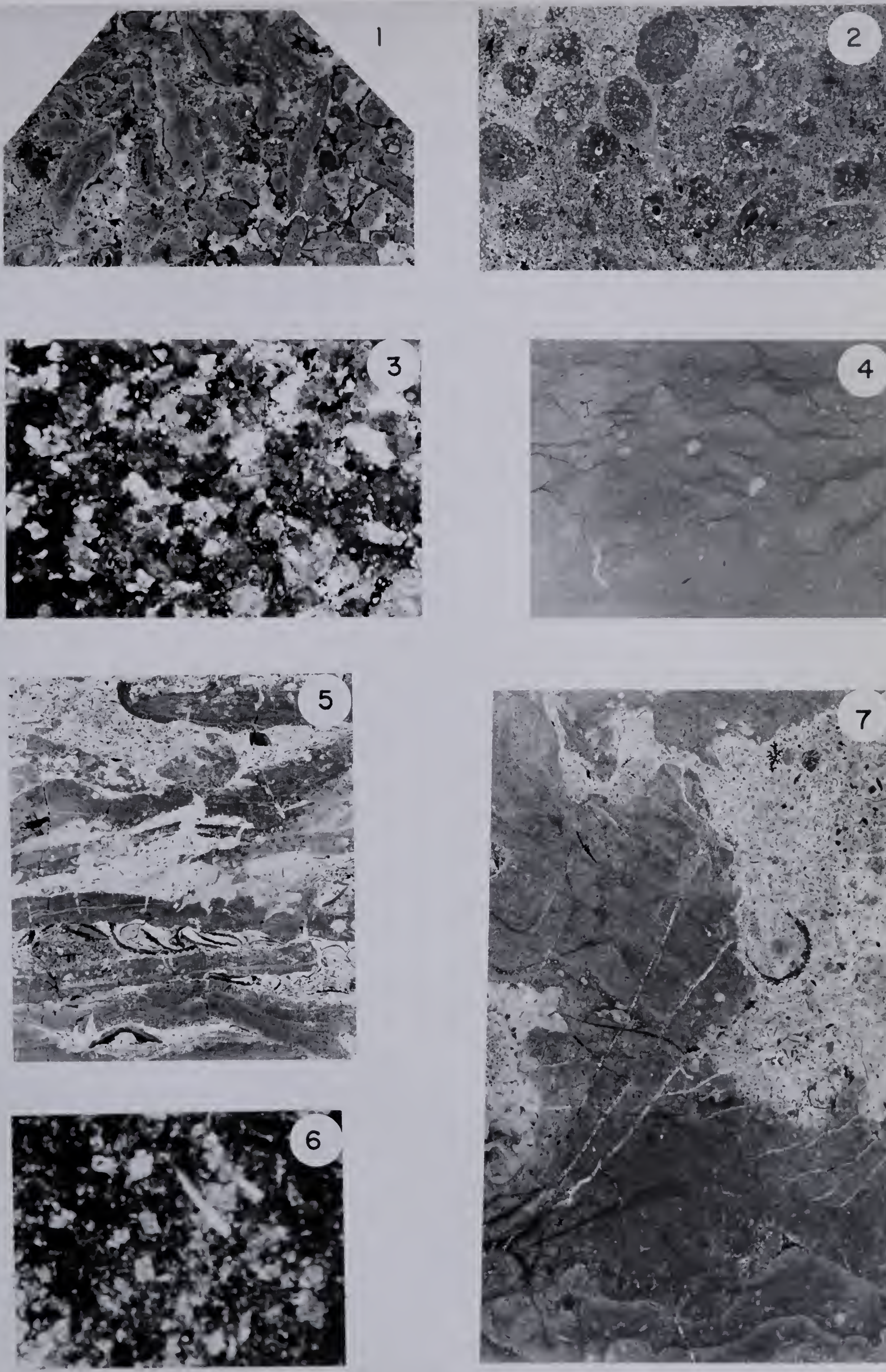

PLATE 9.

EXPLANATION OF PLATE 10

Goose River Rock Types

Figure 1. Facies 16 - Peel of fragmented and coated fossils surrounded by a sand-sized skeletal calcarenite matrix. Note dispersed brachiopod valves. (X1)

Figure 2. Facies 11 - Hand specimen of massive, cabbage-like stromatoporoid with entrapped, sand-sized skeletal grains. High organic and intergranular porosity development. (X1)

Figure 3. Facies 11 - Hand specimen of fragmented tabular stromatoporoids and brachiopods surrounded by a skeletal calcarenite and micritic matrix. Note numerous stylolites. (X1)

Figure 4. Facies 11 - Hand specimen of fragmented branching stromatoporoids and Stachyodes surrounded by skeletal calcarenite groundmass. Note large massive stromatoporoid on right side of photo. Fossils in stylolitic contact. (X1)

Figure 5. Facies 11 - Peel of tabular stromatoporoid in stylolitic contact with underlying fragmented branching stromatoporoids. (X1)

Figure 6. Facies 11 - Hand specimen of algal-stromatoporoid consortium. Note large fossil fragments in a skeletal calcarenite limestone. (X1)

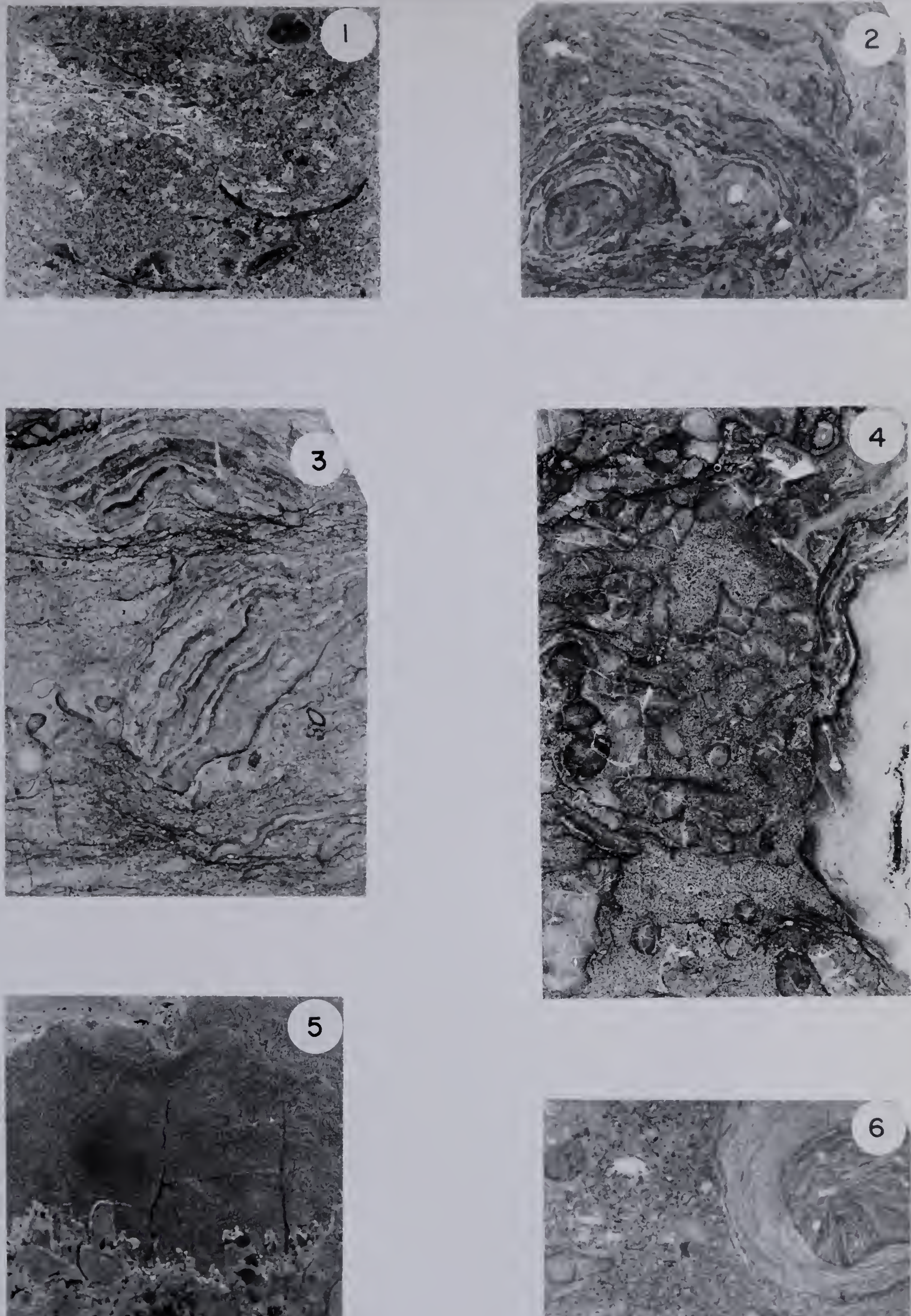

PLATE 10.

EXPLANATION OF PLATE 11

"Virginia Hills" Rock Types

Figure 1. "Reef Rubble Zone" - Peel of pebble sized micrite intraclasts. Note abundant fossils. (X1)

Figure 2. "Virginia Hills Member" - Hand specimen of nodular limestone surrounded by argillaceous matter. (X1)

Figure 3. "Virginia Hills Member" - Hand Specimen showing crinoids and nodular limestone. (X1)

Figure 4. "Coquina Zone" - Peel of fragmented fossil coquina (X2)

Figure 5. "Coquina Zone" - Thin section of brachiopod-crinoid-echonoid-bryozoan coquina surrounded by sparry calcite cement. (X50)

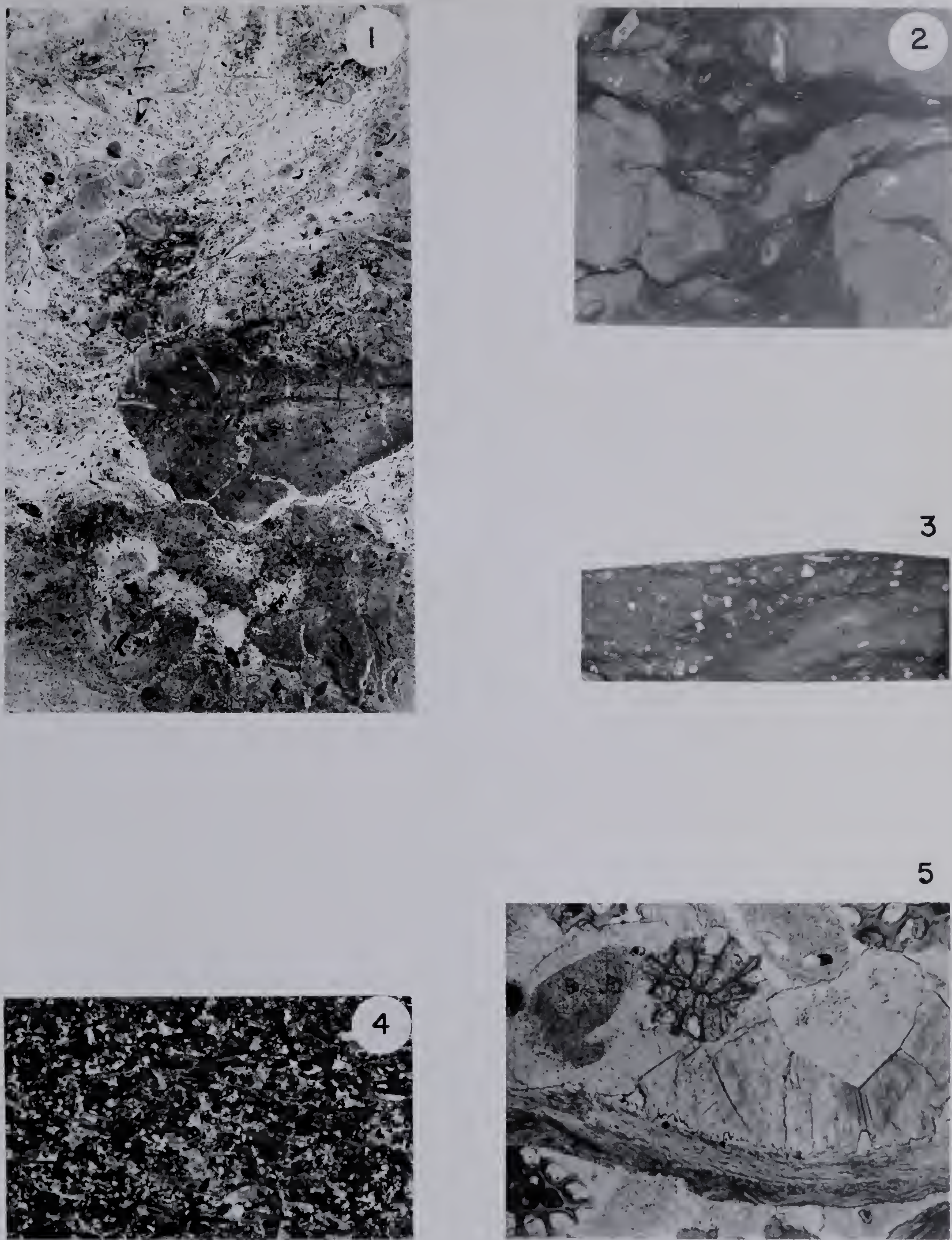

PLATE II.

APPENDIX 1

STAINING TECHNIQUE

Introduction

Following a staining technique outlined by Friedman (1959), various carbonate rocks were stained in order to differentiate dolomite from calcite.

Description of technique

1. The rock specimen was etched in 5% HCL for about 30-40 seconds (the surface was usually polished because a peel had been made, otherwise a raw cut surface was used), then washed off with cold water and allowed to dry at room temperature. A 30 to 40 second etching was sufficient in most cases to bring out the textural and mineralogical relationships.

2. To stain the calcite, a solution of Harris' Hematoxylin was used. The solution is prepared as follows, " .... 50 cc. commercial grade Harris Hematoxylin and 3 cc. 10% HC1 acid" (Friedman, 1959, p. 93). The solution should be shaken well before using.

3. The solution was poured into a pan and the specimen set into it for about three minutes. Calcite develops an even coat of purple colour over its surface while dolomite remains unaffected. Where they is very little dolomite suspected in the rock specimen, potassium ferricyanide should be used because it stains dolomite a deep blue, while the calcite remains unaffected.

APPENDIX 2

ACETATE PEEL TECHNIQUE

Introduction

A number of workers have described acetate peel techniques for sedimentary petrography; namely, Sternberg and Belding (1942), Buehler (1948), Bissell (1957), Beales (1960), Lane (1962) and McCrone (1963). McCrone (1963) relates a brief historical review of former acetate peel techniques which may be of interest to the reader.

Study of carbonate rocks is greatly assisted by well prepared acetate peels because more area is easily provided then by a thin section. Peels may also indicate where thin sections should be made. A big advantage in making peels is the ease and rapidity with which they can be made, and in the case where a particular core cannot be broken, cut, etc., a peel is the ideal way to record a particular section of rock. Other advantages of peels are their ease of future storage, wealth of textural detail provided, and the fact that staining techniques can be applied to them. Peels can then be photographed (get a negative print) and usually are superior in detail in photographed rock specimens.

Materials Required

1. 0.005 inch single-matte commercial acetate film
2. acetone
3. 5% HC1 acid and a saucer shaped dish (large watch glass)
4. half pail of cold water (or a deep pan can be used)
5. box (12" by 14") filled with about two inches of sand
6. pencil, scissors and paper towels

Description of Technique

This technique is a modification of McCrone's (1963) preparation of peel-prints;

1. The rock specimen is first cut to a reasonable size (for polishing purposes) and the edges bevelled on a grind stone (to prevent small chips or rock slivers breaking off during polishing and hence scratching the rock surface - this is most important when using the finer abrasive). A rotating motor-powered table polisher was used.
2. Polish the rock specimen with Nos. 150, 240, 320 and 400 abrasive powders in that order. Wash the rock specimen and rotating disk (plate) liberally with water after using each abrasive powder to get rid of former coarser powder, or else the rock surface will become scratched.
3. After the polishing has been completed have ready a pail of cold water, dish partly filled with 5% HC1 acid and paper towels laid out on a table.
4. Let the rock specimen become moderately dry and then immerse completely in the dish of 5% HC1 acid for a period of 15 to 20 seconds (clayey or bituminous samples require less etching time, while dolomitized samples require more etching - usually you have to experiment two or three times before knowing the correct etching time). Then dip specimen into pail of cold water to wash off the acid.
5. Let the rock specimen dry at room temperature - this takes about ten to fifteen minutes (porous, vuggy or fractured rock surfaces take longer). The surface must be completely dry before applying the acetone or else the peel will not completely adhere to the rock surface.

6. Set the rock specimen in the sand box with the prepared surface facing upwards. Set it relatively level (the sand box holds the rock specimen firmly, and also absorbs excess acetone poured on the surface of the rock). Have ready a piece of 0.005 inch acetate film cut slightly larger than the rock specimen (about 1/4 to 1/2 inch larger on three sides and about one to two inches on the remaining side for labelling purposes).
7. Pour the acetone on the surface of the rock specimen until all of the surface is liberally covered and glistening. Take the acetate film and warp it gently in the shape of a U with the matte side facing downwards and lay it down on the rock surface starting from the centre of the rock surface thus preventing the formation of air bubbles. The acetone dissolves the contact side of the acetate film so that it flows and conforms to the microscopic textural relief of the specimen. Do not press the acetate film on the rock surface.
8. Let dry for fifteen minutes and then, starting at one edge, take the peel off slowly.
9. Trim the edges of the peel, label it, and then put it between pages of a book or between two plates of glass to prevent curling.
10. The peel can then be photographed, (a negative photograph is produced) or it can be photographed against a dark background to obtain a positive photograph (Easton, 1942).